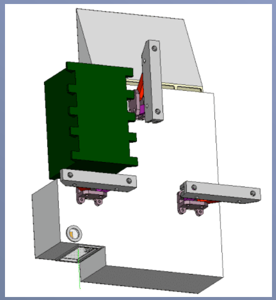
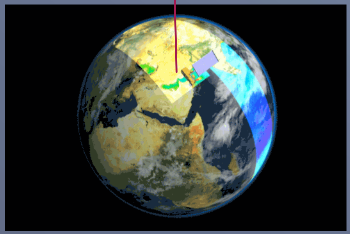
Regional Smog Ozone and Its Production
Can Be Made Broadly and Inexpensively Visible!

What do we need?
What do we not need?
Can we get this with easily implemented, robust, technology?

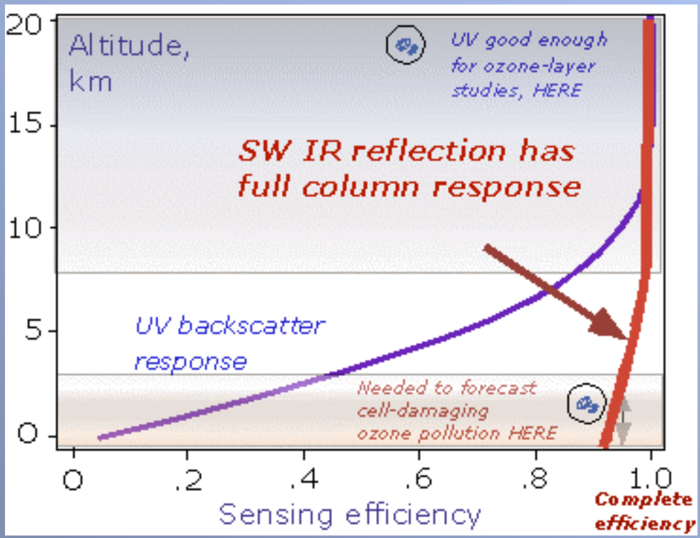


R. B. Chatfield, Ames Research Center, NASA

J. B. Kumer, J. L. Mergenthaler, A. E. Roche,
Lockheed Martin Advanced Technology Ctr., Palo Alto
LOCKHEED MARTIN



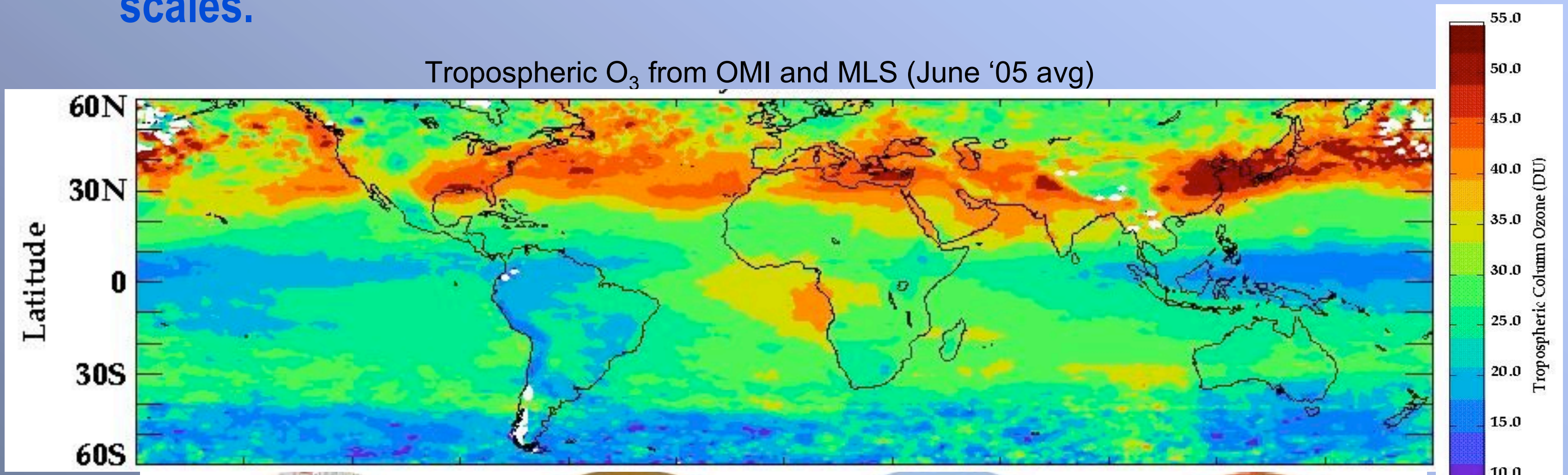
Harvard University, Earth and Planetary Science, Colloquium, Sept. 14, 2007



Science Overview I

- **Local and regional emissions impact ozone and aerosol on local to global scales.**

Tropospheric O_3 from OMI and MLS (June '05 avg)



[Ziemke et al., 2006]

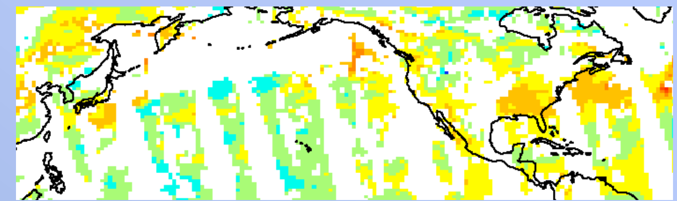
- Understanding the "Globalization of air pollution" is explicitly one of the Grand Challenges of the Integrated Global Observing Strategy (IGOS) atmospheric chemistry community (IGACO, 2004).

Concept Guide

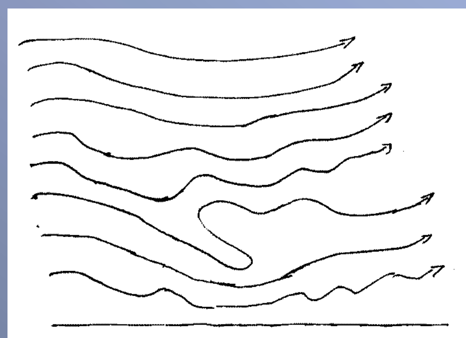
- Our (shared) vision: tracking ozone and its production

UV monitor
[HCHO] monitor
[NO] monitor

$\Big\} \xrightarrow{f_1} P^{\circ}_{O_3} \xrightarrow{\gamma} P_{O_3}$

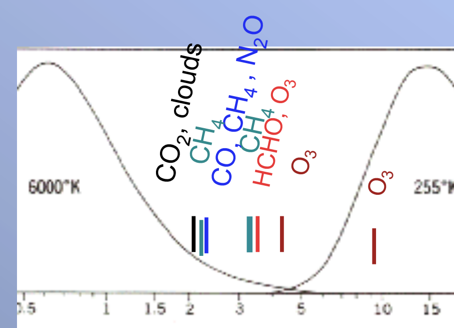


- Sensing BL smog ozone rapidly and inexpensively

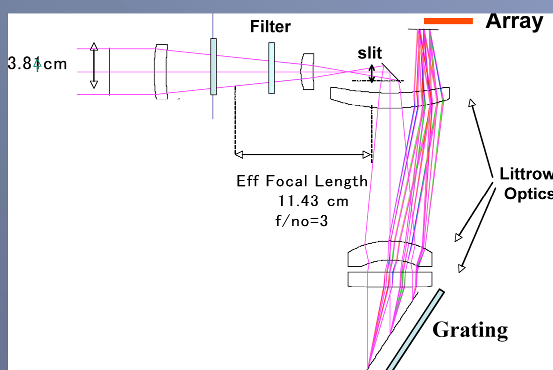


- Sensing ozone production

- New ways of highlighting smog (LT) ozone



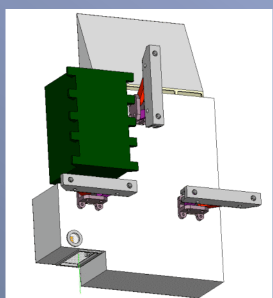
- New wavelength windows in the "dark regions"



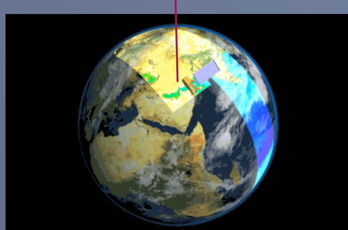
- Newly simple-design instrumental techniques

Guide to Instrument Concepts

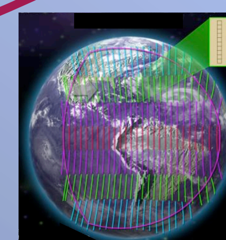
- TinyTIMS: Fastest, least expensive way to powerful new low earth orbit measurements: O_3 and HCHO
- - 20 kg, in the nano-sat to small-sat category
- Either “bridging technology” (2 year) or still-economical small 4-6 year Earth-tracking

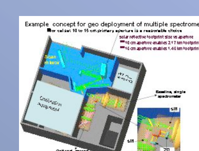


- TIMS: a compact multi-species single-concept package:
  - HCHO and O_3 (tropospheric resolution)
  - ideal mate for a very compact, inexpensive UV sensor
  - CO and CH_4 with vertical tropospheric resolution
  - modest-accuracy CO_2 added inexpensively
  - Most/All(?) of GACM global tropospheric chemistry recommendation

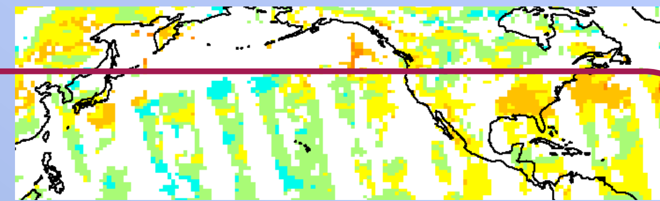


- GEOTIMS: similar compact multi-species single-concept package for piggyback, 87 kg
  - HCHO and O_3 (tropospheric resolution)
  - ideal mate for a very compact, inexpensive UV sensor
  - CO and CH_4 with vertical tropospheric resolution
  - modest-accuracy CO_2 conceivable





Concept Guide



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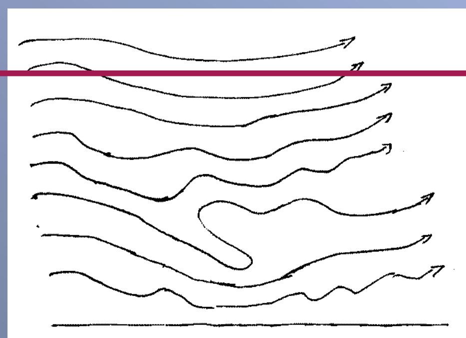
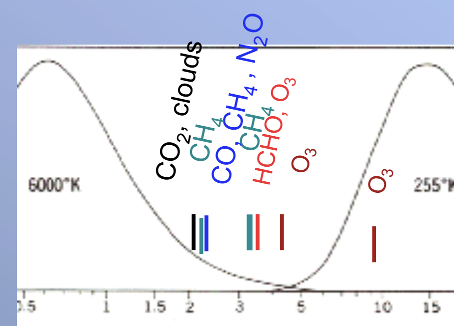
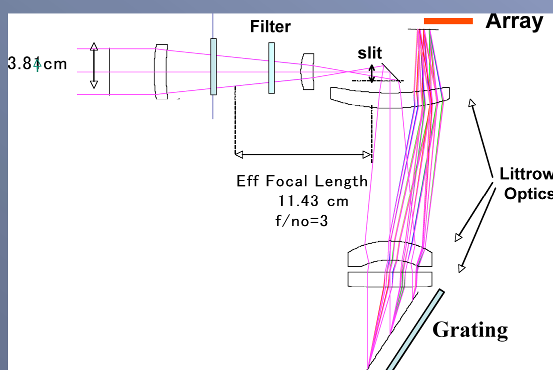


- Sensing ozone production

- New ways of highlighting smog (LT) ozone

- New wavelength windows in the "dark regions"





- Newly simple-design instrumental techniques

Our (shared) vision: tracking ozone and its production: Major Challenges

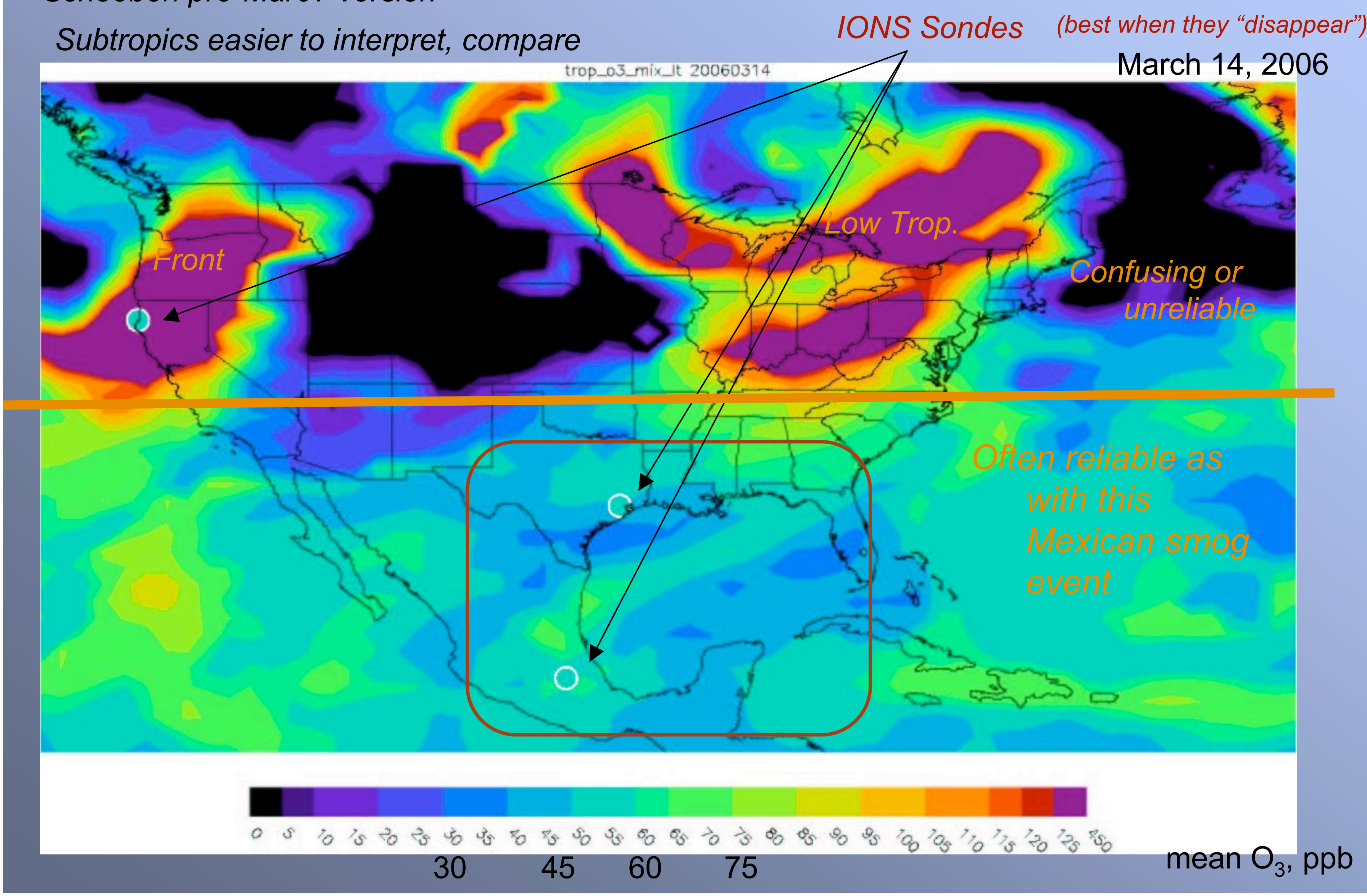
- Transport of ozone: uncertainties in regional and intercontinental transport: Follow patterns of ozone and update models: daily correction and long-term process improvement.

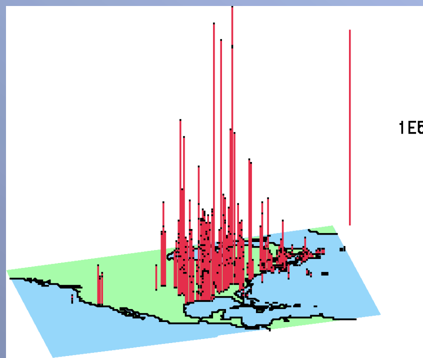
- Production of ozone: Need to understand where our prediction models fail due to inadequacies in emissions, in reaction chemistry, or in mixing of precursors

Need daily or near-daily maps for ozone's weather-driven changes:

Schoeberl pre-Mar07 version

Subtropics easier to interpret, compare

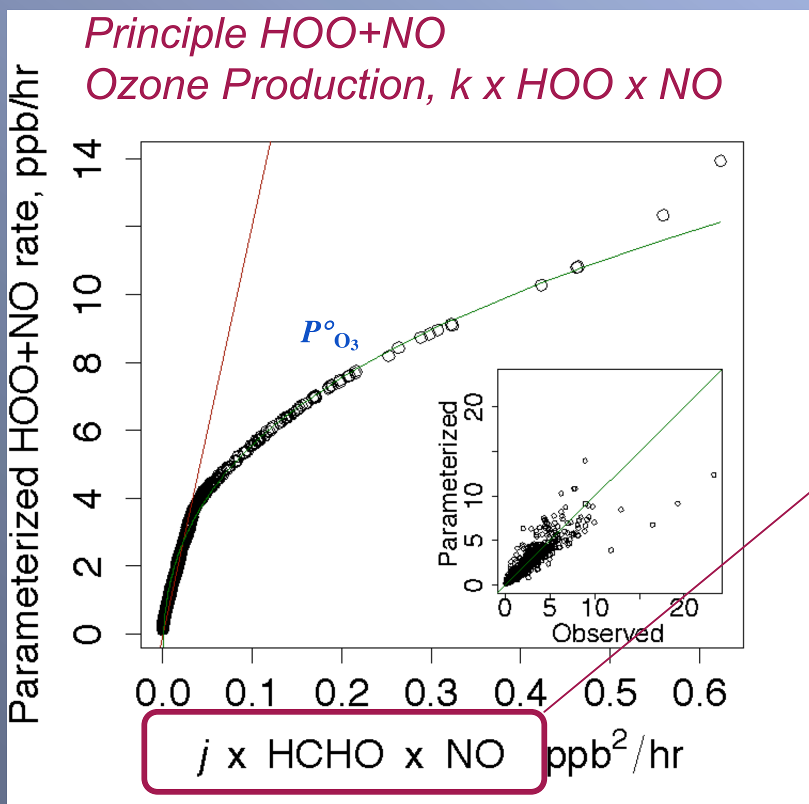




Sensing Smog Ozone Production

Ozone production rate is highly variable even at regional scale … sampled by DC-8, INTEX-NA

POGO–FAN: Production of Ozone by Gauging Oxidation; Formaldehyde and NO



This is not a POGO lecture!

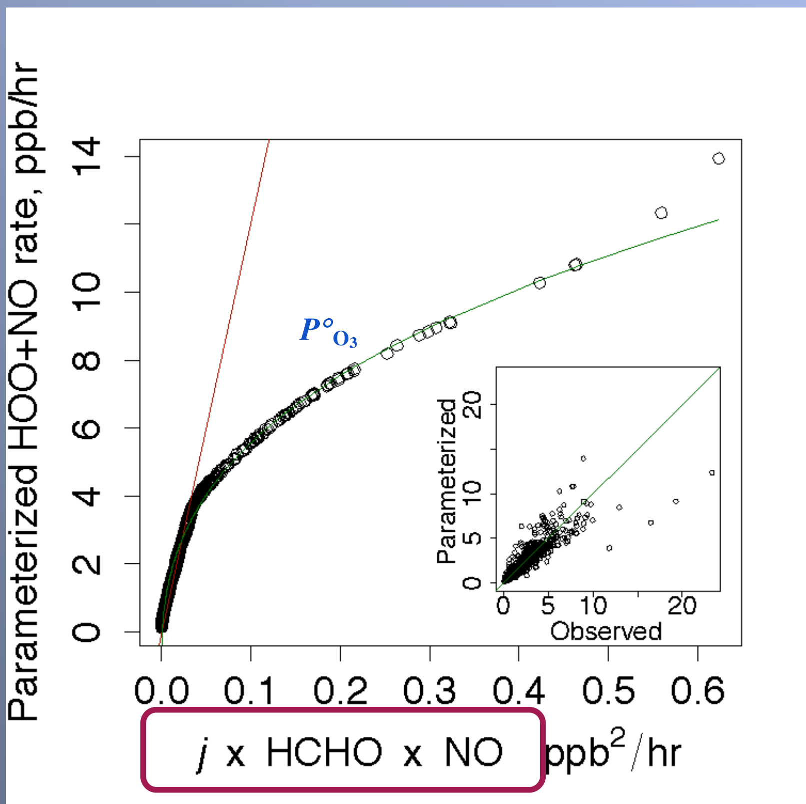
POGO-FAN asserts that THIS product gives a very general parameterization of smog ozone production

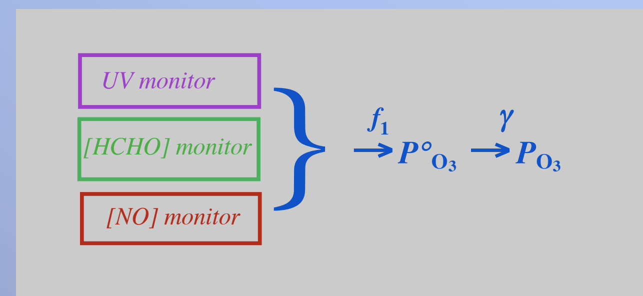
j x HCHO gives production of HOO

j x HCHO *and* NO help determine destruction rate of HOO,

NO gives NO

Measurements of Nitrogen oxides, along with “Gauges” of Organic-Oxidation <=> HOO Radical Production Help Constrain Smog Ozone Simulations … Strongly





What Space-borne obs can provide:

NO_2 relatable to NO,

UV photolysis rate information,

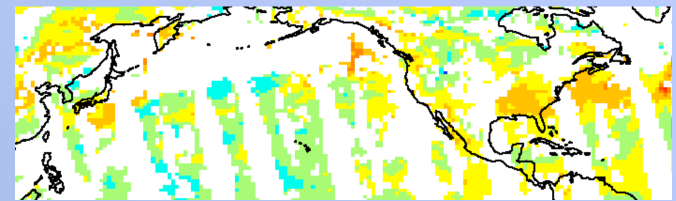
HCHO,

with j_{HCHO}, a gauge of organic oxidation rate

Indicators of organic complexity?

glyoxal, methyl glyoxal?

Concept Guide



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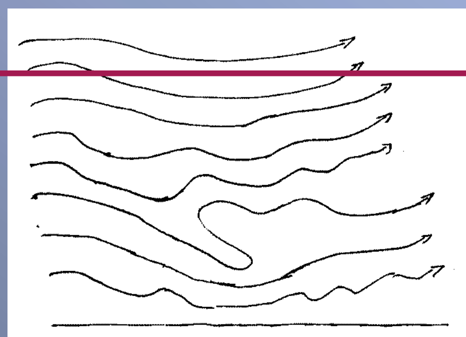
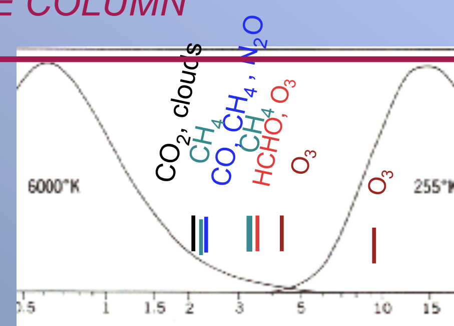
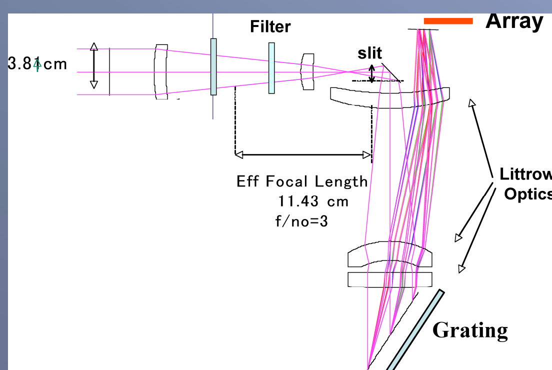


- Sensing ozone production
  - New ways of highlighting smog (LT) ozone:

    THESIS:
    WE DO NOT REQUIRE EXPENSIVE STRATOSPHERIC OZONE INSTRUMENTS IN ORDER TO SUBTRACT THE LARGE OVERLAYING OZONE COLUMN

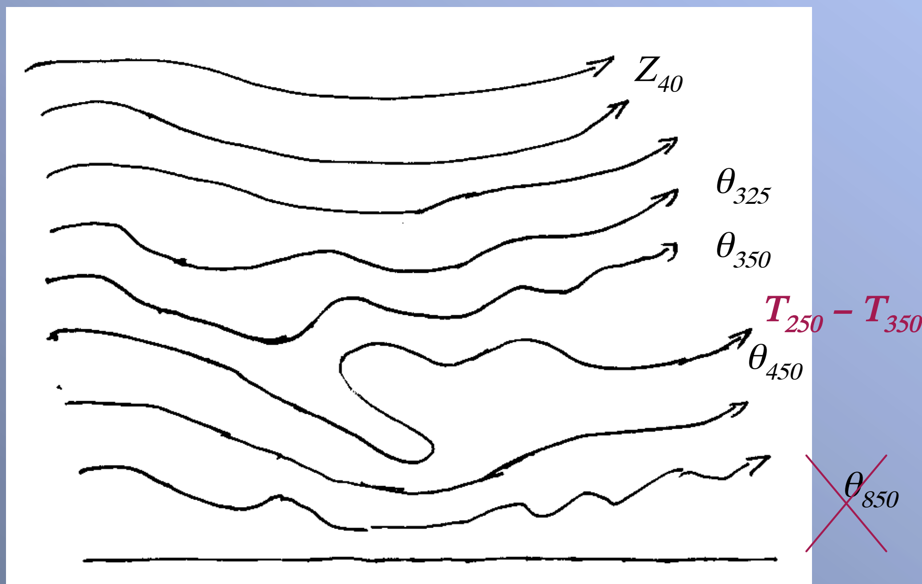
- New wavelength windows in the “dark regions”





- Newly simple-design instrumental techniques

Vertical Distribution of Ozone from Column Ozone Measurements: Stratosphere and "Distraction" Removal: OMI ozone and AIRS Temperatures



Specific technique "projection pursuit regression" — roughly analogous to empirical orthogonal functions, but assembling combinations of those explaining variables (θ's) that have the most explanatory value for the explained variable, total ozone.

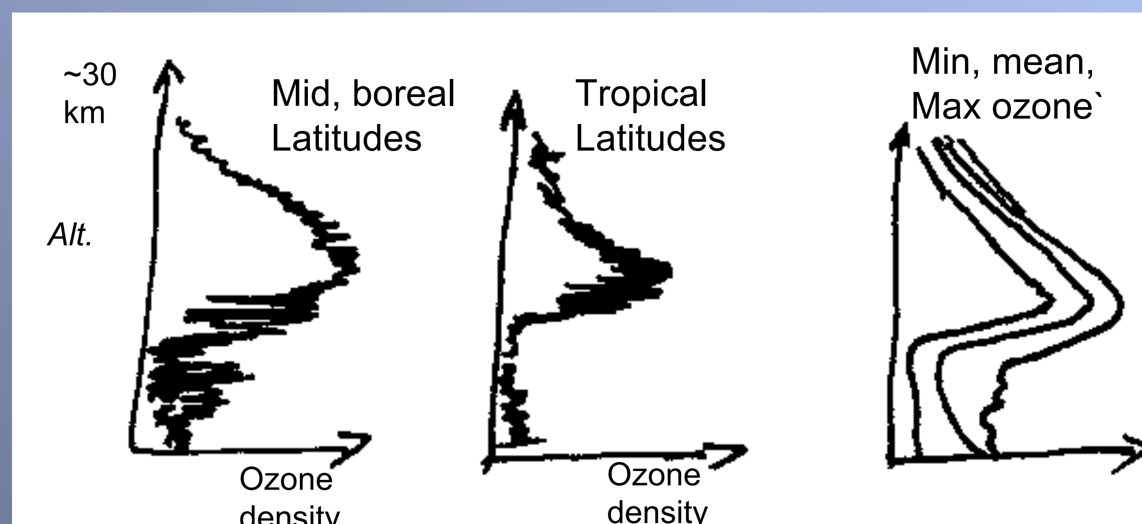
Sums: average properties of layers

Differences of T's: Lapse rate

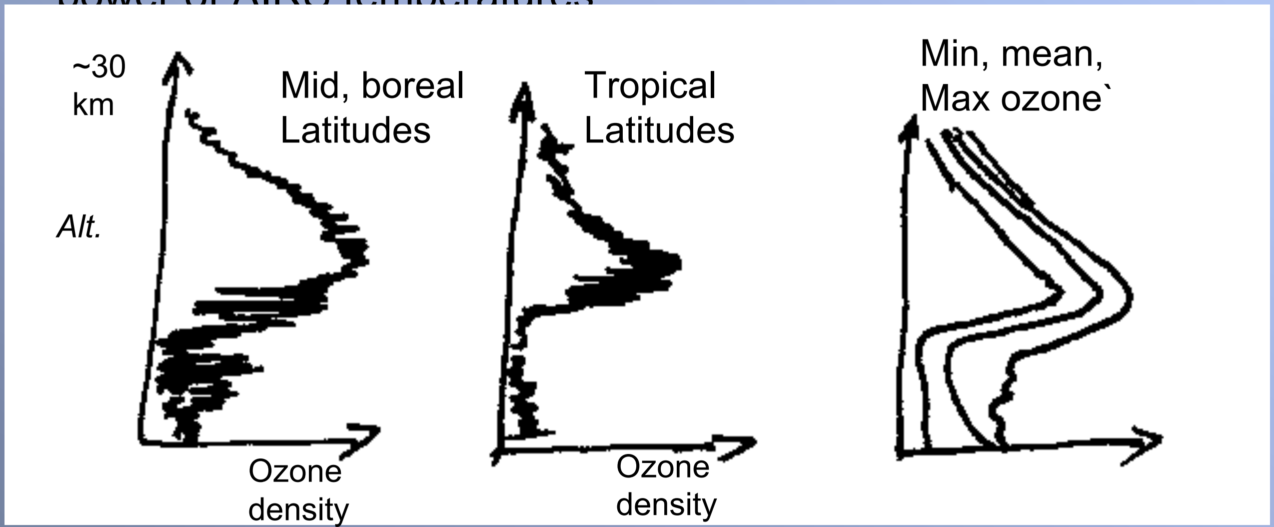
Do not include lower-tropos. variables

Statistical relationships depend on co-variations over six weeks of dynamical variables, T's, θ's, Z's (varied expressions of AIRS temperatures)

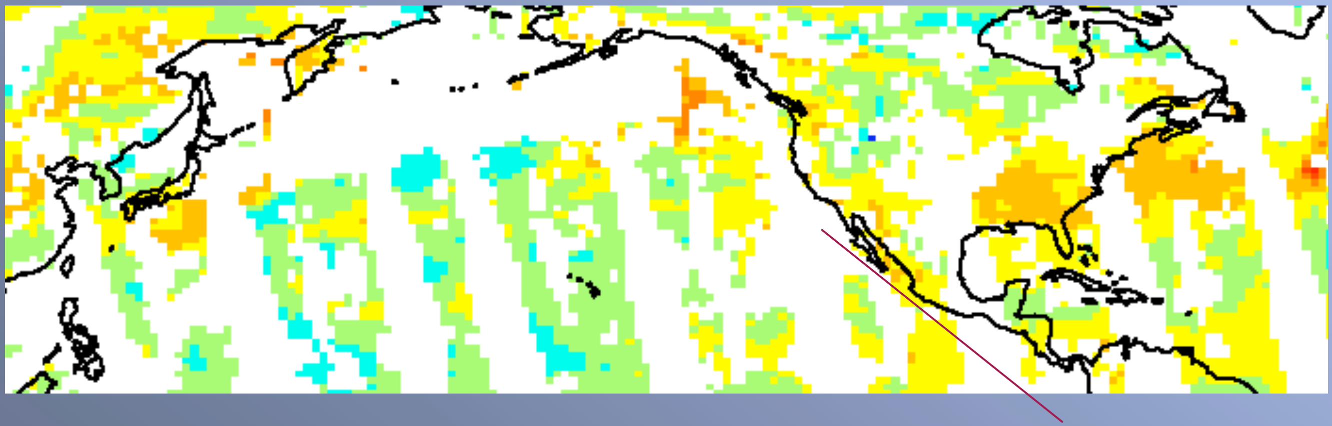
Some automatic fitting, some choices for small sets of variables which might work best



Both vertical and horizontal variations contribute to the explaining power of AIRS temperatures



Missing areas due to Narrow swath of AIRS, clouds



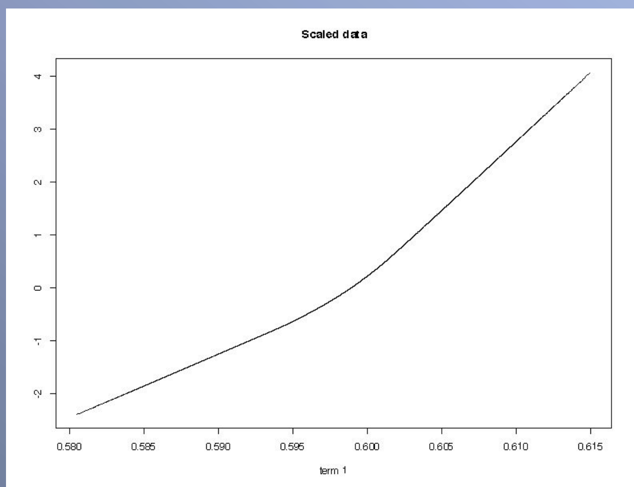
Algorithm should soon handle low clouds, such as here

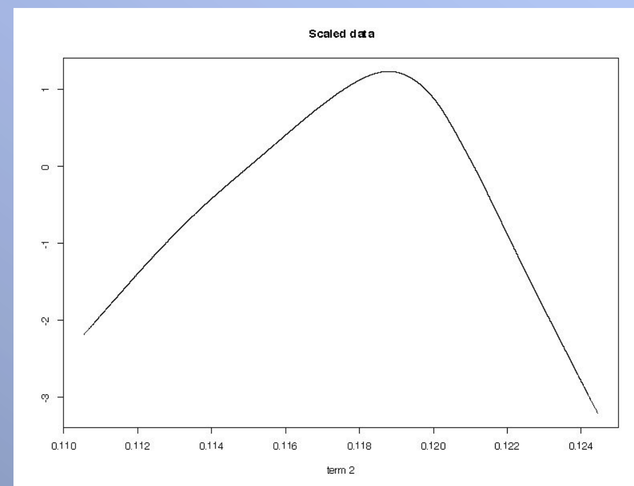
Example of Stratospheric Fit: August, 2006

AIRS Variable	term 1	term 2	term 3	term 4	term 5	term 6
T_{450}	-0.01	-0.03	-0.01	-0.20	-0.07	0.33
T_{350}	-0.33	-0.02	0.04	0.03	0.40	-0.01
T_{275}	0.25	0.06	-0.01	-0.15	-0.59	0.40
T_{225}	-0.22	-0.06	0.04	-0.04	0.29	-0.20
Z_{175}	-0.23	-0.03	0.01	0.34	0.18	-0.53
Z_{60}	0.45	0.79	-0.73	-0.58	-0.26	0.58
Z_{40}	0.72	-0.61	0.68	0.70	-0.55	-0.28
latitude	-0.02	0.01	0.00	-0.01	0.01	0.01
Relative Contribution	0.05	0.03	0.02	0.01	0.01	.004
249317 fit points	r = 0.92	r^2 = 0.84				

- Why such a large variance explained? => Both vertical and horizontal (N/S) fit
- Any fitting of the troposphere is accidental … accdents can happen: I.e., correlations of structure between tropposphere and stratosphere (particullarly UT?)

Example of Stratospheric Fit: First and second combinations

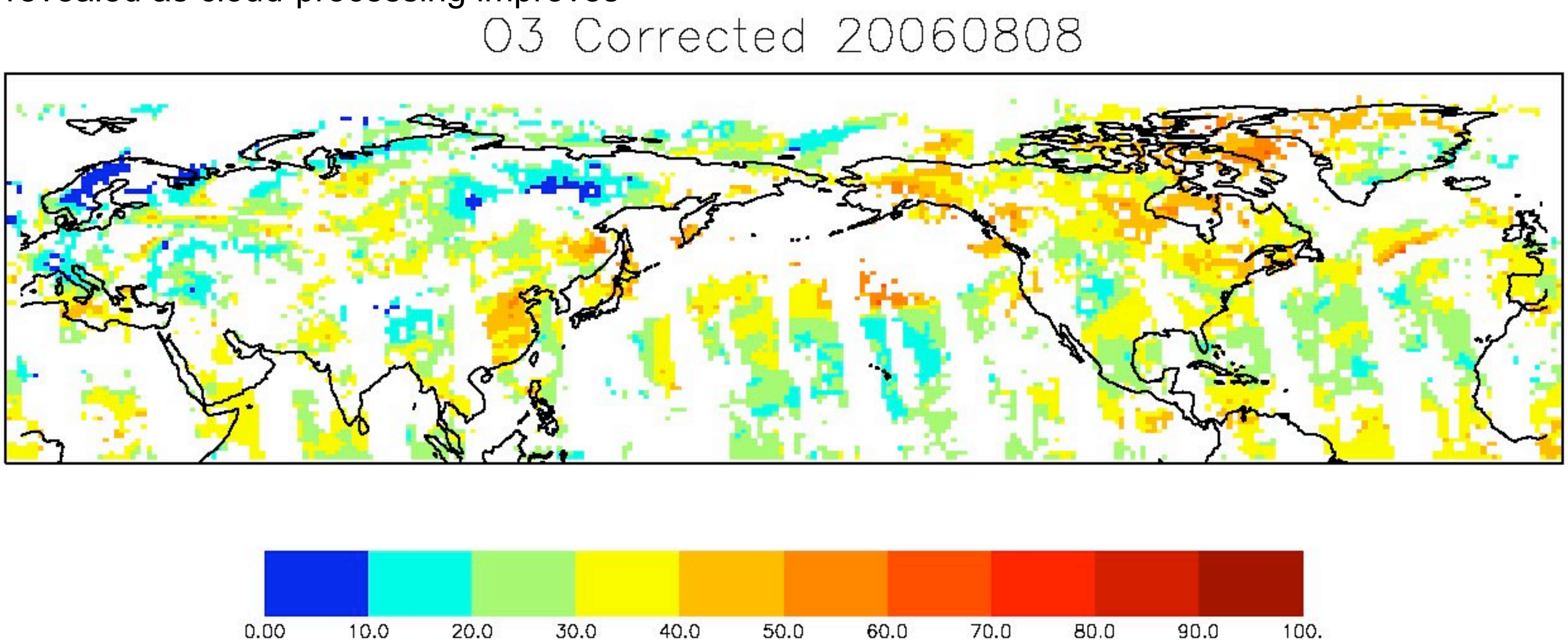




Response function for linear combinations of variables. In this situation, where we expect stratospheric ozone and stratospheric dynamical variables to exhibit simple relationships, the response curves are simple combinations of linear functions: recall that the first projection pursuit directions attempt to summarize all the most significant information, and often these are simple combinations or contrasts (differences).

“Overnight” Tropospheric Ozone Remainder: not explained by stratospheric structure

- Higher ozone areas are frequently found near and offshore from China, SE USA, and Europe. Stratus-cloud regions (off LA, Portugal) should be revealed as cloud-processing improves



- Preliminary Anlysis: There are known processing differences in the Boreal/Arctic between AIRS and OMI products used , … and more relationships to explore

Where we are

- Smog ozone and broader tropospheric ozone can be studied with good measurements of column ozone

  - Do NOT need limb-scan or even short-wave UV

  (e.g., no *scanning* MLS or HIRDLS or SAGE)

  - DO NEED good column-ozone measurement(s)

  - DO NEED AIRS / IASI Thermal IR Sounders for “dynamics” (θ)

  CAN certainly use thermal IR (AIRS / IASI) ozone distribution information

  CAN certainly use UV information (e.g. X. Liu) on vertical distribution

  Extra IR and UV information are complementary to the dynamical correlation method:

  They love averaging, it depends on variance,

  Smog ozone amounts are difficulty and are limited by “noise”

  It is worthwhile to add all we (economically) can

- Smog ozone production needs NO_2, HCHO, and perhaps UV

Concept Guide

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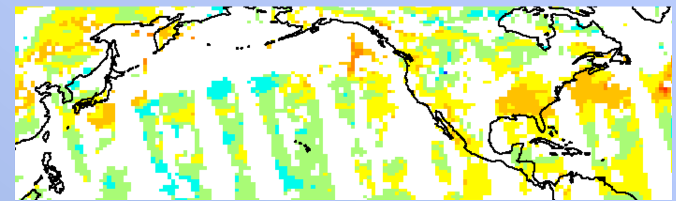

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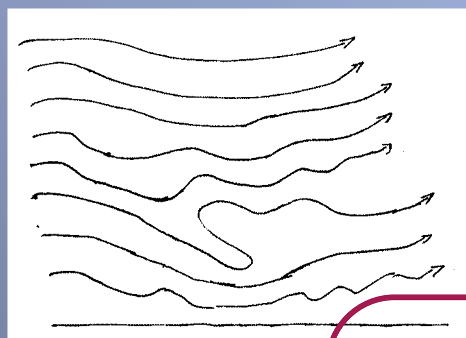

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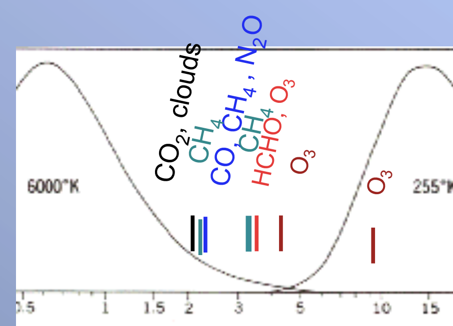
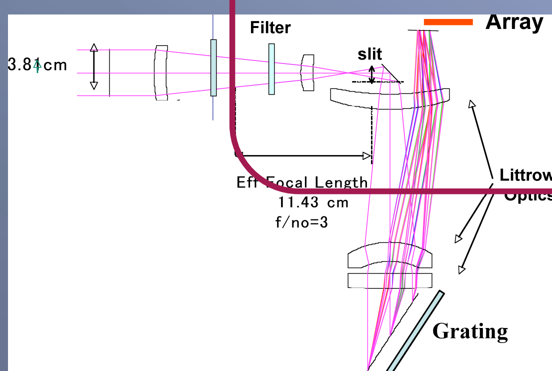
- New ways of highlighting smog (LT) ozone

- New wavelength windows in the "dark regions"





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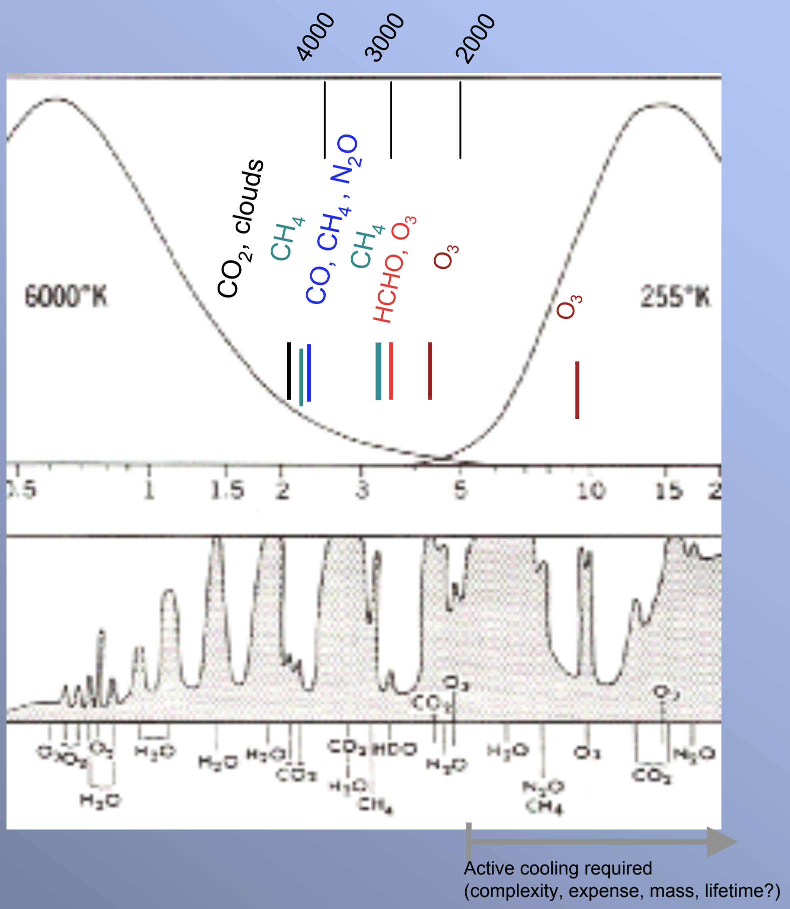
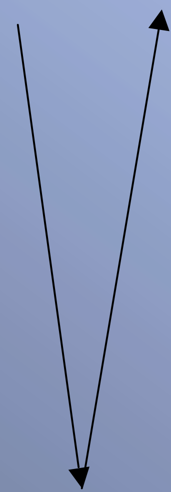
Wavelengths and Species (ii)

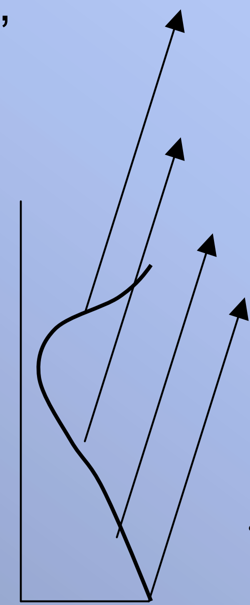


R. Chatfield, NASA Ames: TIMS: The Promise of IR Global Mapping Spectrometry

Basics of Estimation — Clouds hurt, clouds help



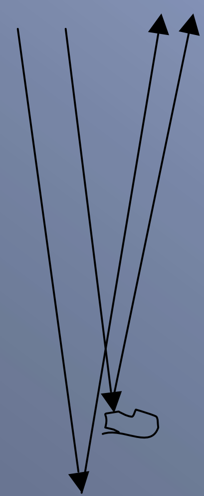
- Direct absorption of solar radiation;
- Works to nearly 4 μm



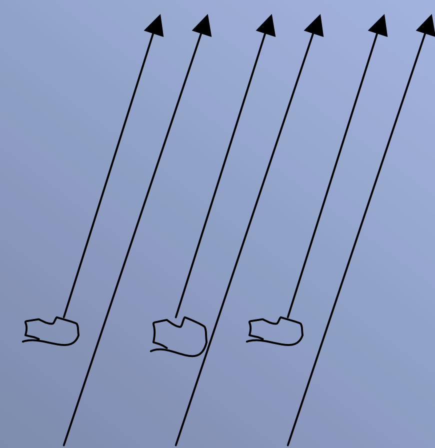
- Thermal emission using atmospheric T to provide a vertical scale:
- Works from somewhere above 3 μm

- Note: Some mixing of information from regions of similar temperature

- Zero information at surface



- Cloud chopping to find concentra-ions in PBL



- Cloud clearing to estimate simple mixture effects from different levels

“Full-column” and True Full-column (IR-based) Total Ozone Column

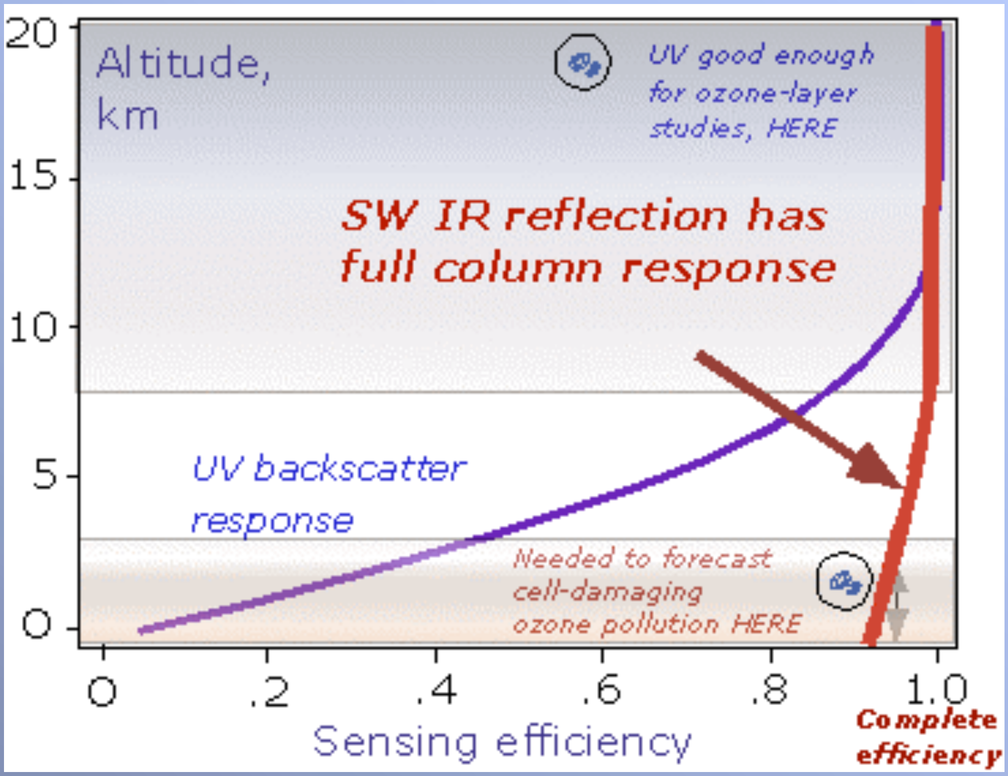
Note

• that while UV at ~0.32 μm, techniques claim ~1% precision, ~2-4% is due to a-priori in lower troposphere, … more when columns are quoted in the presence of clouds

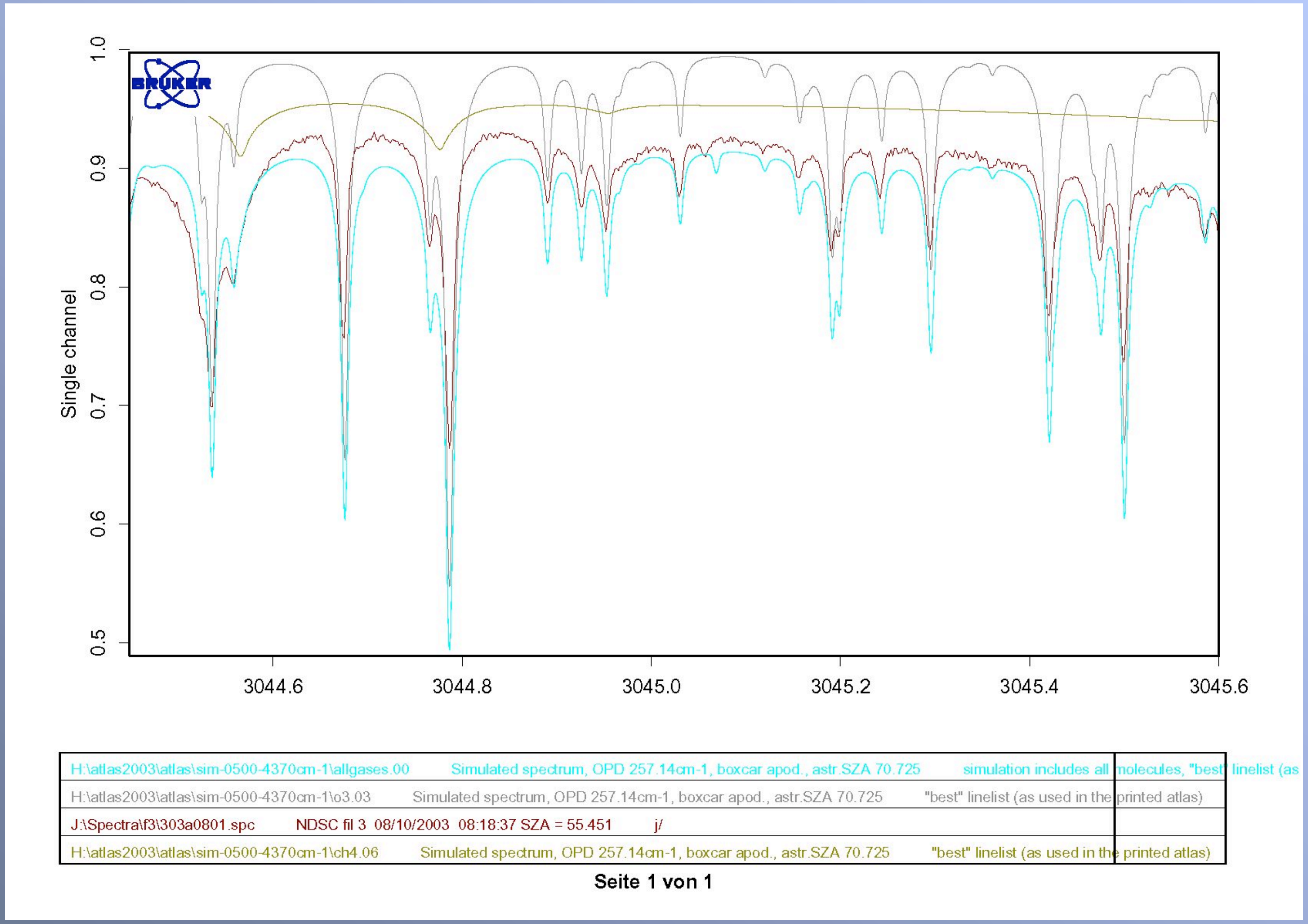
• 2-3% precision for IR at 3.57 μm, but more weak lines might be “harvested” at some cost.

• Combination of 0.32 and 3.57 gives better precision and a difference measurement for the lower troposphere (LT)

• Need 1-4% total column precision to get LT ozone: Using thermal IR helps greatly, describing 1.5 to 5 km region.

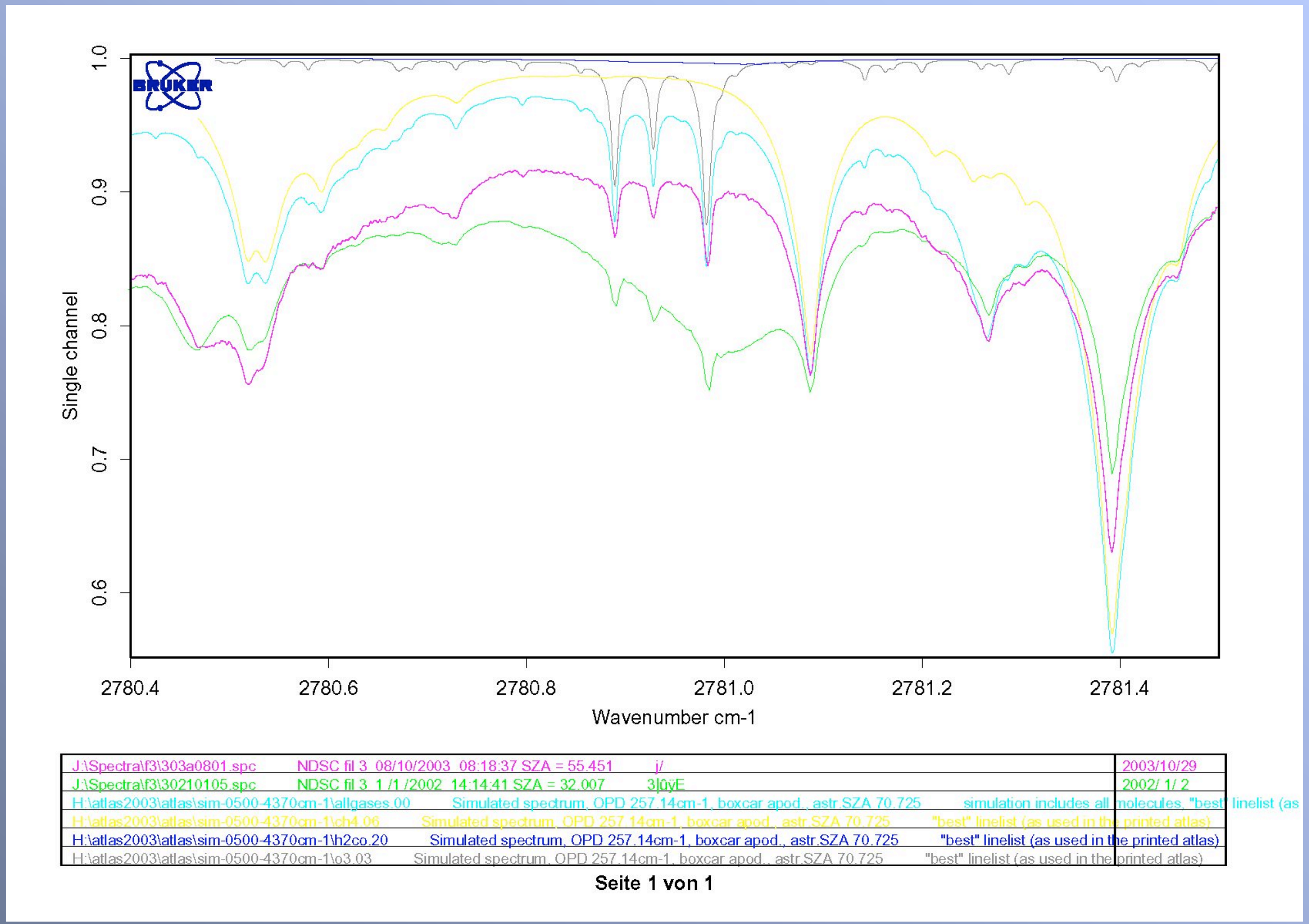


High information for O3 retrieval at ~ 3.57



•Nick Jones, U. Wollongong typical spectra but more weak lines might be “harvested” at some cost.

High information for HCHO retrieval at ~ 3.57



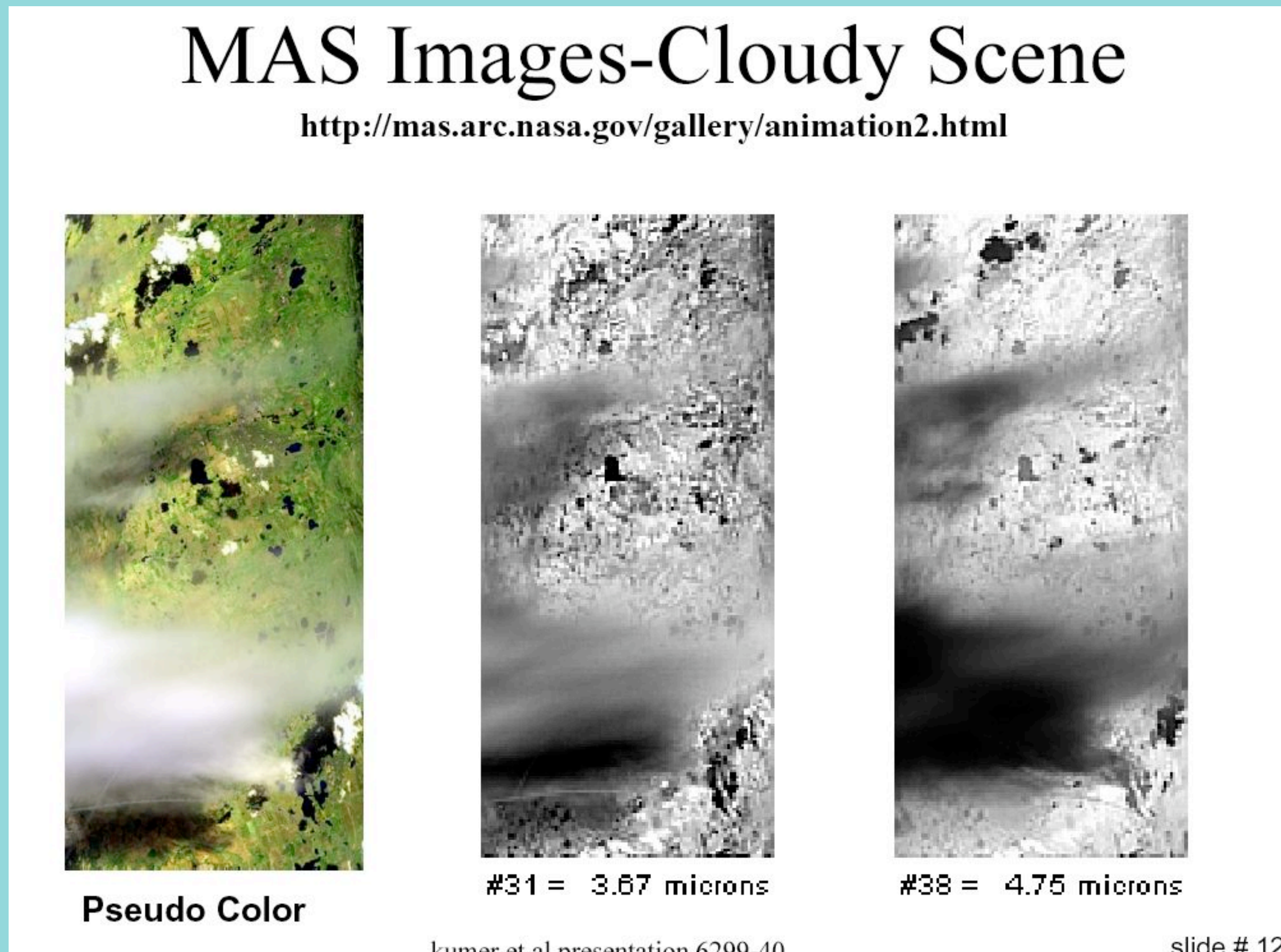
- Nick Jones, U. Wollongong typical spectra and one fire-emissions spectra.

Difficulties and opportunities of the infrared upward-radiance-minimum neighborhood:

Past ~2 mm, albedo is low but sufficient, 1.5–10%

At 3.6, there are many bright spots, while clouds are gray

MODIS Airborne Simulator scenes of Eastern North America at 3.7

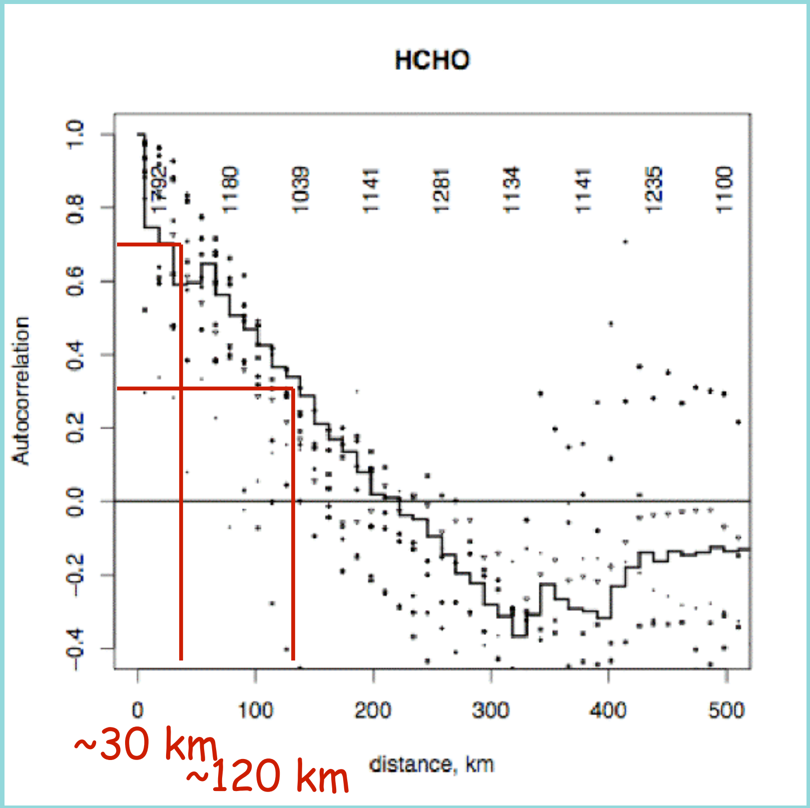


Jeff Myers,
R. Domiguez,
NASA Ames /
UCSC

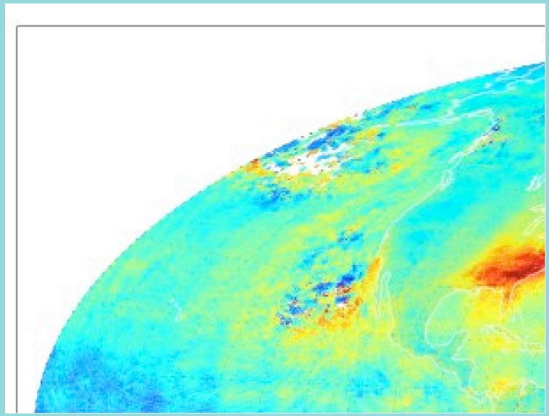
- *Must understand desired sampling scale and confidence in interpolation*
- *Can we use cloud-slicing for lowest kilometer?*

Chatfield et al., 2006a

Autocorrelation scales for HCHO



If informative bright albedo spots occur every 20–50 km (they do) we have useful estimates



Averaged OMI HCHO data <u>does not show detail</u>

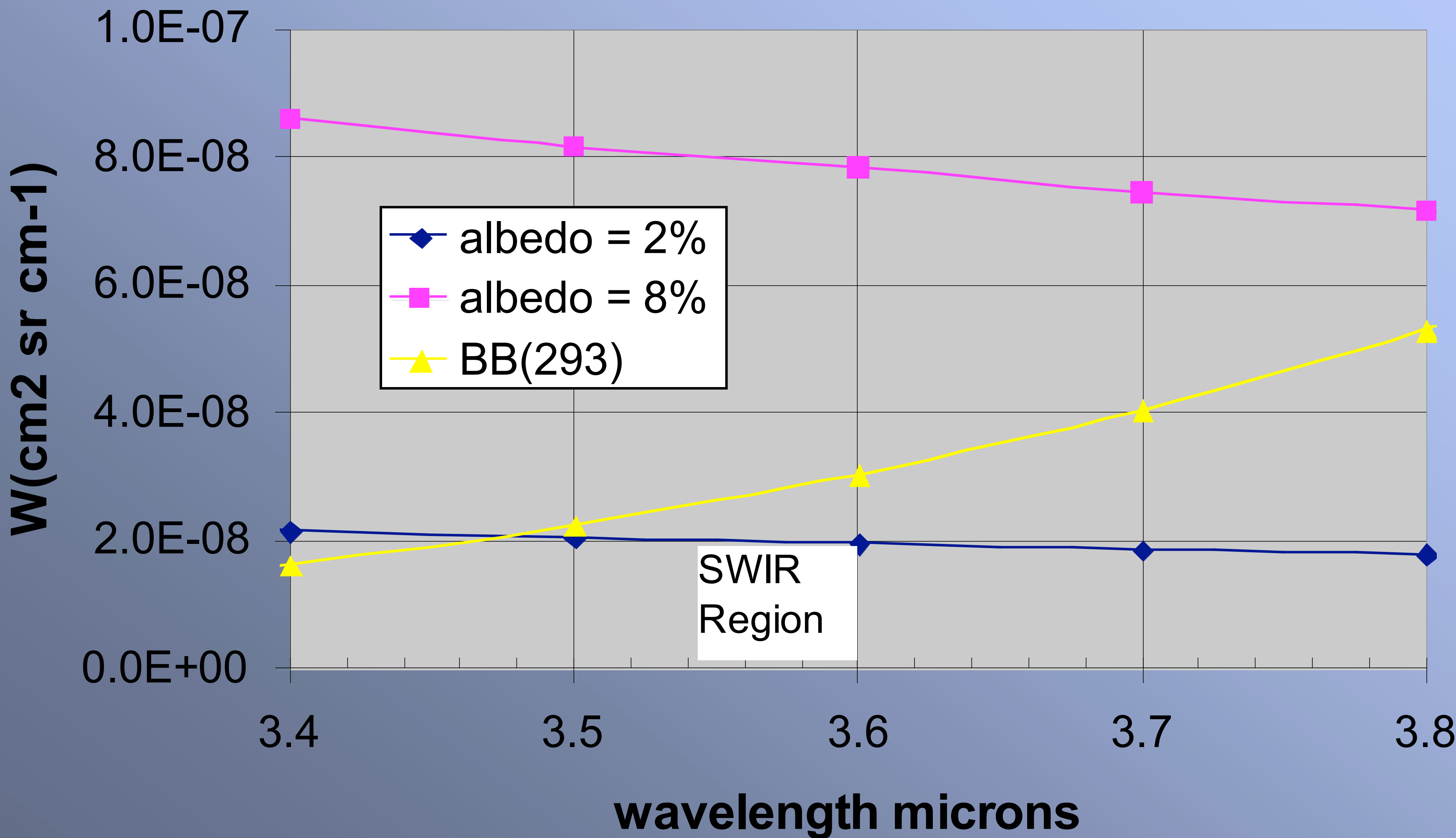
Spatial Autocorrelation from DC-8 boundary-layer sampling suggests *both narrow* and *broad* geographical features

Thanks to T. Korosu; early slide

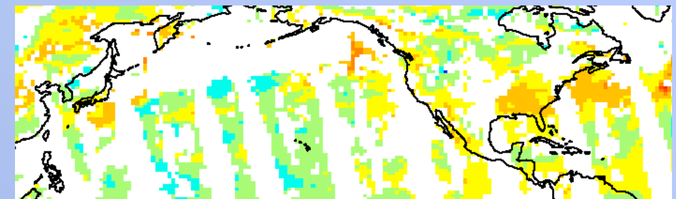
compare 293K black body with solar reflected

BB_{T293K} vs $(1+1/\cos(\theta_{solz}))\alpha\cos(\theta_{solz})\Pi F_{solar}/\pi$ for $\alpha = 2\%$ and 8%

where $\theta_{solz}=45^{o}$ and ΠF_{solar} is the solar irradiance



Concept Guide

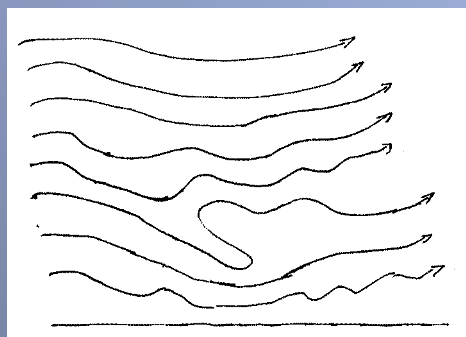


- Our (shared) vision: tracking ozone and its production

UV monitor
[HCHO] monitor
[NO] monitor

$$\left.\begin{array}{l}\text{UV monitor}\\ \text{[HCHO] monitor}\\ \text{[NO] monitor}\end{array}\right\}\xrightarrow{f_1} P^{\circ}_{O_3}\xrightarrow{\gamma} P_{O_3}$$

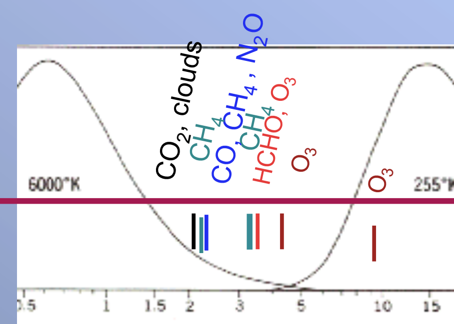
- Sensing BL smog ozone rapidly and inexpensively

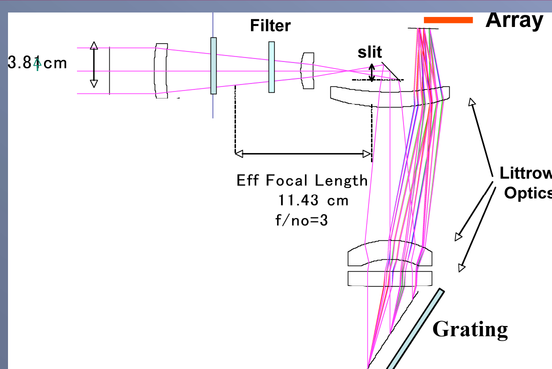


- Sensing ozone production

- New ways of highlighting smog (LT) ozone

- New wavelength windows in the “dark regions”

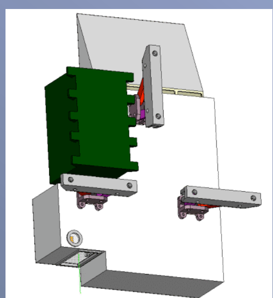




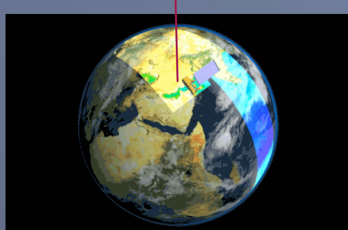
- Newly simple-design instrumental techniques
- Intro to instrument concepts

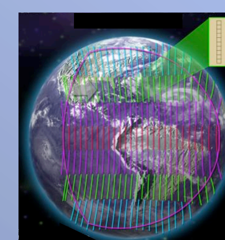
Guide to Instrument Concepts

- TinyTIMS: Fastest, least expensive way to powerful new low earth orbit measurements: O_3 and HCHO
- - 20 kg, in the nano-sat to small-sat category
- Either “bridging technology” (2 year) or still-economical small 4-6 year Earth-tracking



- TIMS: a compact multi-species single-concept package:
  - HCHO and O_3 (tropospheric resolution)
  - ideal mate for a very compact, inexpensive UV sensor
  - CO and CH_4 with vertical tropospheric resolution
  - modest-accuracy CO_2 added inexpensively
  - Most/All(?) of GACM global tropospheric chemistry recommendation





- GEOTIMS: similar compact multi-species single-concept package for piggyback, 87 kg
  - HCHO and O_3 (tropospheric resolution)
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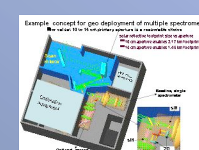
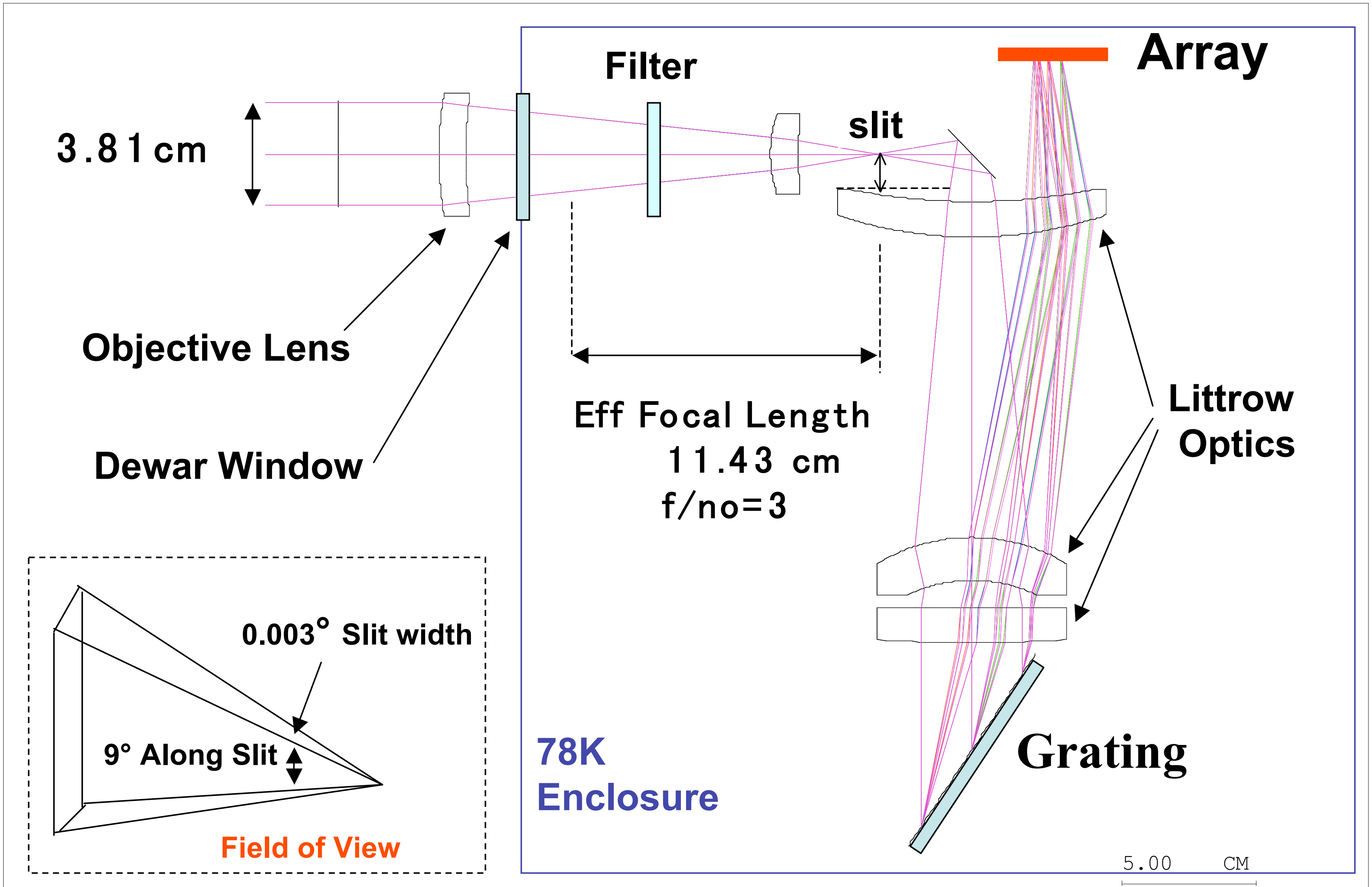
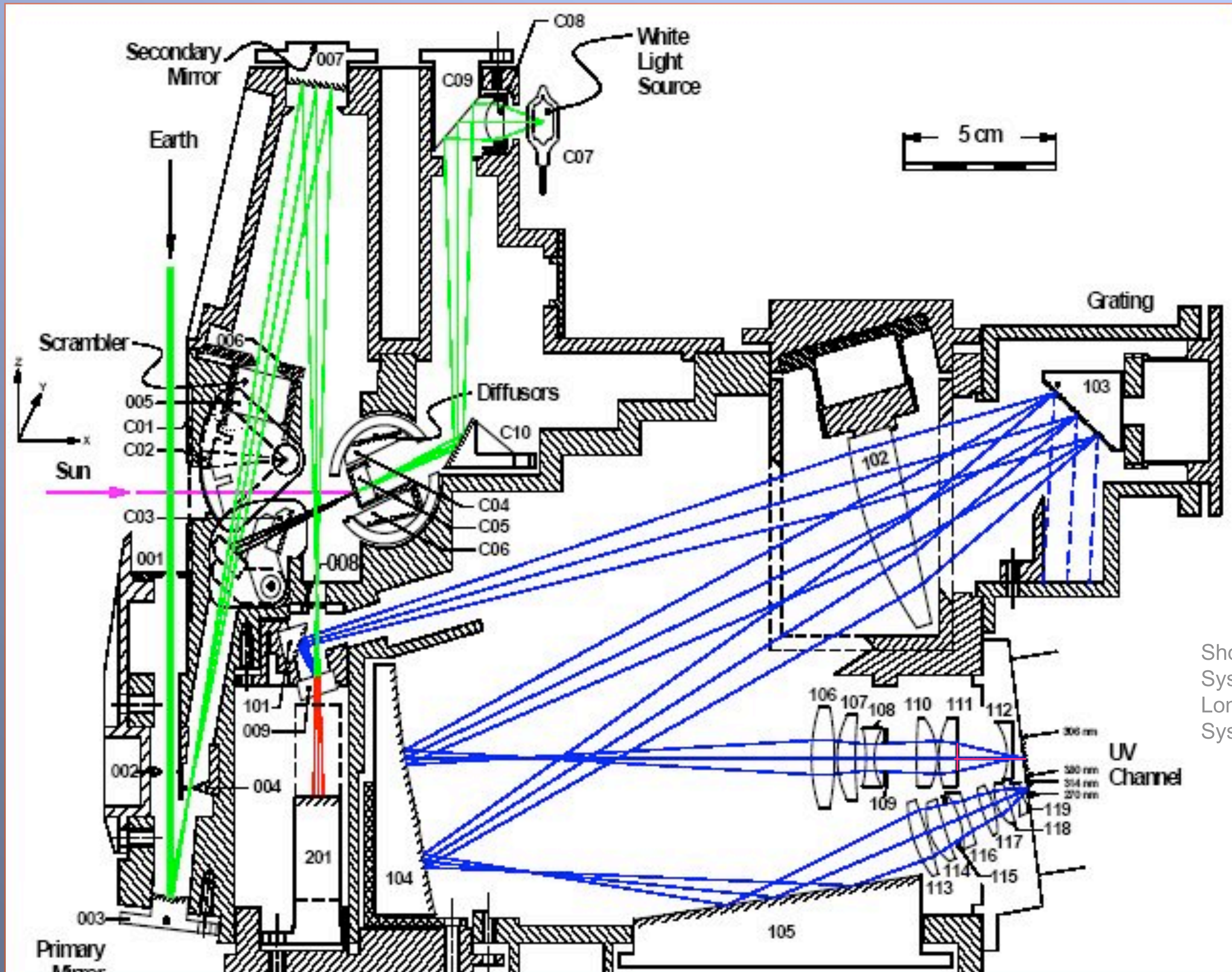
  - CO and CH_4 with vertical tropospheric resolution
  - modest-accuracy CO_2 conceivable



Laboratory demonstration grating mapping spectrometer (GMS) Optical schematic



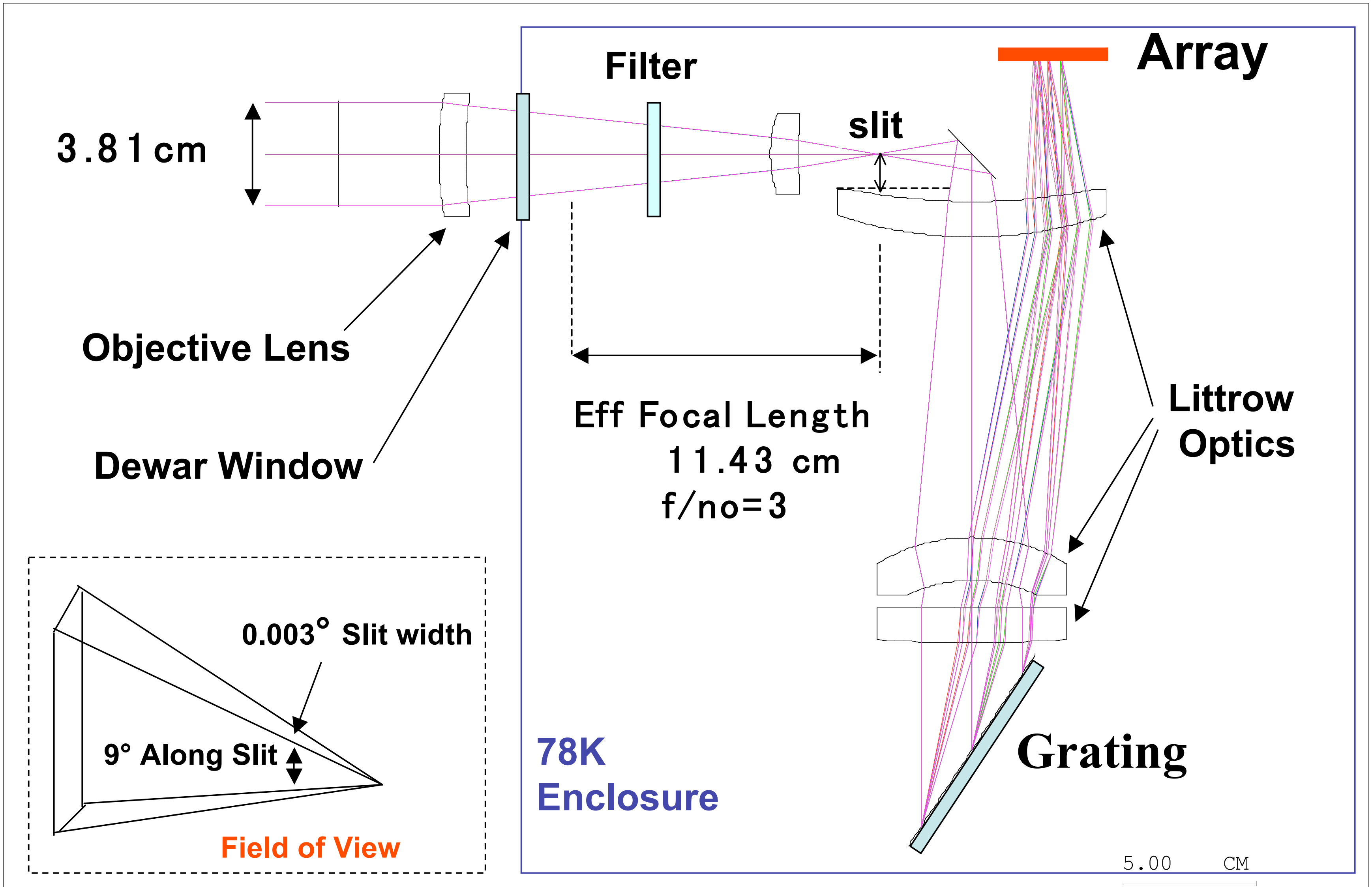
Demonstrates the measurement principle



Short uv 270 – 314 nm
System f/# ~0.8 ?
Long uv 306 – 380
System f/# ~ 3.2 ?

OMI optical design schematic, note: [1] tiny (~ 1.55 mm) crosstrack aperture dimension [2] large f#s in the front end optics, and to& from grating, [3] short UV system f/# about 4 times < the long UV f/# (⇒ narrower swath & boosted signal/px for the short UV

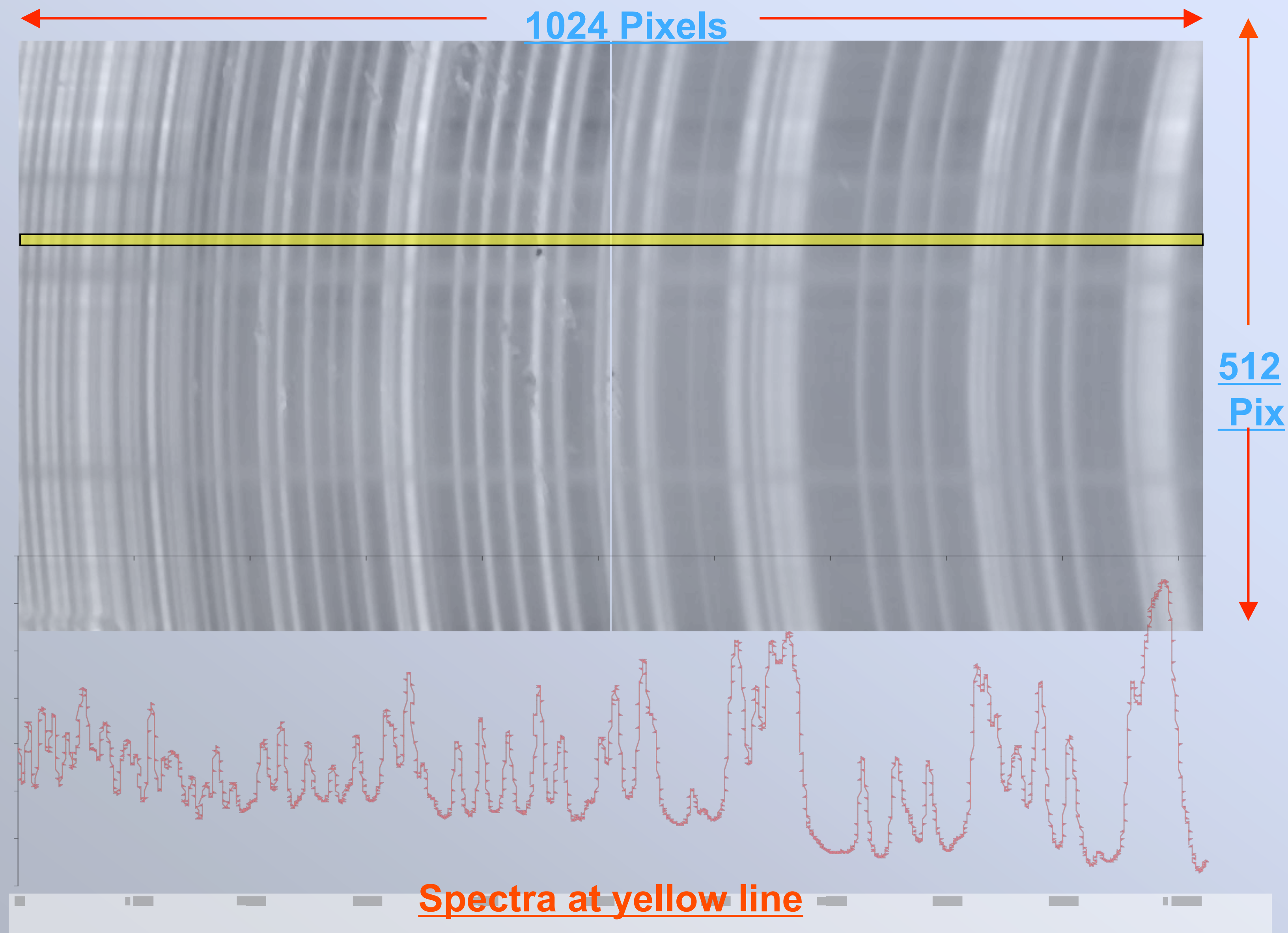
Laboratory demonstration grating mapping spectrometer (GMS) Optical schematic



Demonstrates the measurement principle

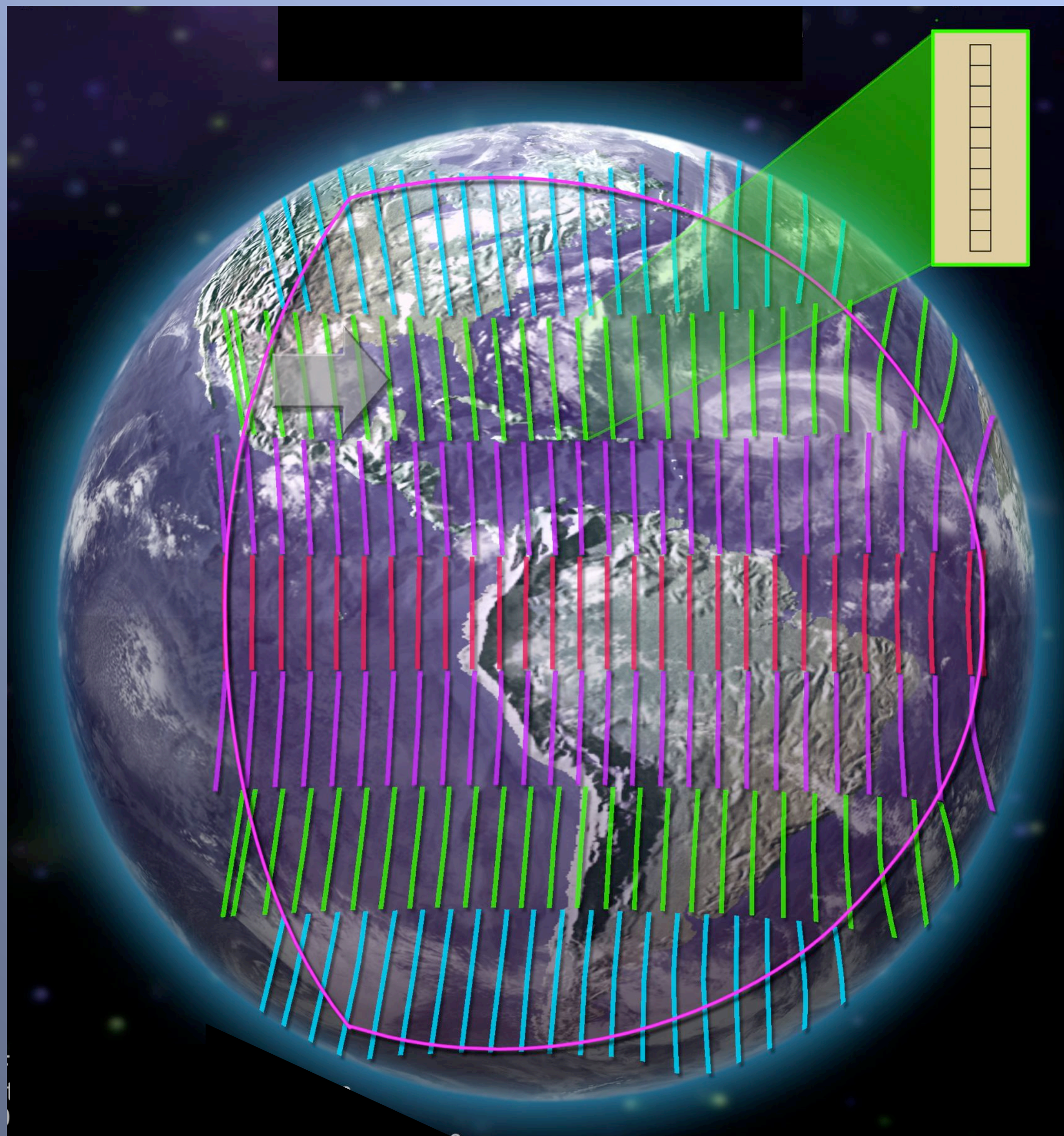
Why can we expect low-cost missions?
What gives the mass, cost, power savings?

- Concentration on narrow, very informative spectral intervals
- Resolution equaling or surpassing FTIR’s but with fewer apodization, transform, … intricacies of FTIR
- Simple, robust construction: difficulties like “smile” are more economically corrected in software than by massive designs.
- Compact Littrow grating design folds back optical path for a small, Light instrument
- For LEO: no moving parts to obtain wide scan
- One moving part: calibration
- For GEO, add well-understood cross-path scanner
- Extremely flexible adaptation for new species and wavelength ranges



2-Quadrant Image of Zenith SKY IR Emission Spectra

Example of spectrometer from GOES east



- Next slide shows a plausible instrument approach to utilize a grating mapping spectrometer[s] in a geo deployed instrument

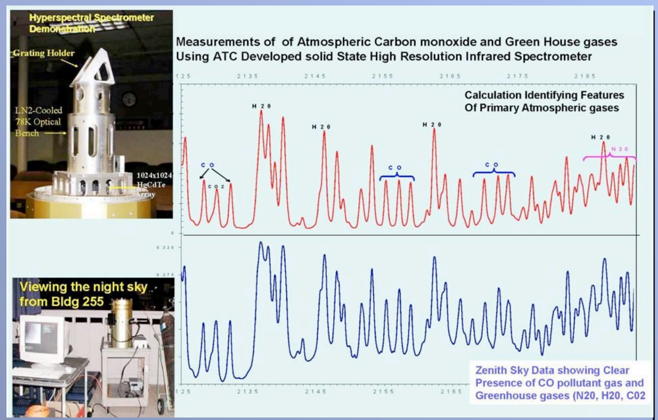
- Two moving parts:
  - scanner (well-tested)
  - calibration on/off

HQ Costing Study: Alternative Instrument Concepts (2/2)

GEO TIMS

Mass: est 87 kg
Power: est 160 W
Volume: 0.43 m x 0.24 m x 0.67m

TIMS = Tropospheric Infrared mapping Spectrometers



Clear sky spectral data near 4.7 um compared with a model. Data, with $\nu \sim 0.5\ cm^{-1}$, were obtained with demonstration predecessor to the IIP GMS.

Features of the TIMS Measurement Concept

Employs two grating mapping spectrometers (GMS);

- Utilize separate 9 cm apertures & scan mirrors
- Each has 2 channels: 3.6 & 2.3 μm and 9.6 & 4.7 μm
- 3.6 μm channel uses solar reflective (SR) and thermal IR signal to obtain
  - Column $\mathbf{O_3}$ with sensitivity in the BL
  - **HCHO** in full and partial column
- The 9.6 μm channel provides layers of O_3 in the troposphere and above, and also
  - BL O_3 by combined retrieval with SR data
- The 2.3 and 4.7 μm channels provide **CO** in 3 layers, including the BL with precision better than 10%.
- Ancillary retrievals of BL & profile $\mathbf{CH_4}$ and $\mathbf{H_2O}$, and $\mathbf{N_2O}$ & $\mathbf{CO_2}$ column

Performance Data

Measurements: -- • field of regard = 22° diameter and • **footprint** size @ nadir = **2.5 km** @ 2.3 μm; **5.0 km** @ 3.6 and 4.7 μm; and **10.0 km** @ 9.6 μm

- Areal coverage = 2500 km x 2500 km per 20 minutes
- Threshold spectral range $\nu_1 \rightarrow \nu_2$, resolution ($\Delta\nu$) & NEdN characteristics

channel	$\nu_1 \rightarrow \nu_2$ (cm^{-1})	$\Delta\nu$ (cm^{-1})	NEdN ($nW/(cm^2\ sr\ cm^{-1})$)
~ 2.3 μm	4281 to 4301	0.13	1.0
~ 3.6 μm	2778 to 2791	0.13	1.0
~ 4.7 μm	2112 to 2160	0.20	1.0
~ 9.5 μm	1043 to 1075	0.10	2.0

Retrieval expectations:

- $\mathbf{O_3}$ **including the BL** and 3 additional layers below 22 km with precision <5% in the latter
- **CO in the BL** and 2 layers above with respective precisions the order 10, 5 and 3%
- **HCHO** with column precision < 4 x 10^{15} /cm^2.

Technology Development Needs

1. IIP demonstration (2006-2008) of the TIMS GMS will result in TRL 5+
   a. Includes GMS operating near 2.3 μm & 4.7 μm.
   - portable to facilitate field measurements
   b. CO retrieval from atmospheric measurements
   - validated by retrievals with data from Denver University FTS
2. 9.6 μm channel demonstration
   a. Large format, low noise array with cutoff ~ 10.5 μm
   b. Suitable detector array has been demonstrated on a high noise direct injection mux
   - we anticipate no problem on low noise, low light mux

➢ **Not chosen for design study owing to relatively lower TRL,~4, but should be considered for future.**

GEO Performance Data

Measurements: -- • field of regard = 22^o diameter and

• **f o o t print** size ***at nadir*** = **2.5 km** @ 2.3 μm;

5.0 km @ 3.6 and 4.7 μm;

and **10.0 km** @ 9.6 μm

• Areal coverage = 2500 km x 2500 km per 20 minutes

• Threshold spectral range $\nu_1 \rightarrow \nu_2$, resolution ($\Delta\nu$) & NEdN characteristics

channel	$\nu_1 \rightarrow \nu_2$ (cm^{-1})	$\Delta\nu$ (cm^{-1})	NEdN (nW/(cm^2 sr cm^{-1}))
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~ 9.5 μm	1043 to 1075	0.10	2.0

Retrieval expectations:

• **O_3 including the BL** and 3 additional layers below 22 km with precision <5% in the latter:
i.e., < 5% in 0 to ~3 km region: both column (3.6) and thermal (9.5) contribute
Aggregating four 5-km footprints should

• **CO in the BL** and 2 layers above with respective precisions the order 10, 5 and 3%

• **HCHO** with column precision < 4 x 10^{15} /cm^2.
Height information from day and night retrievals.

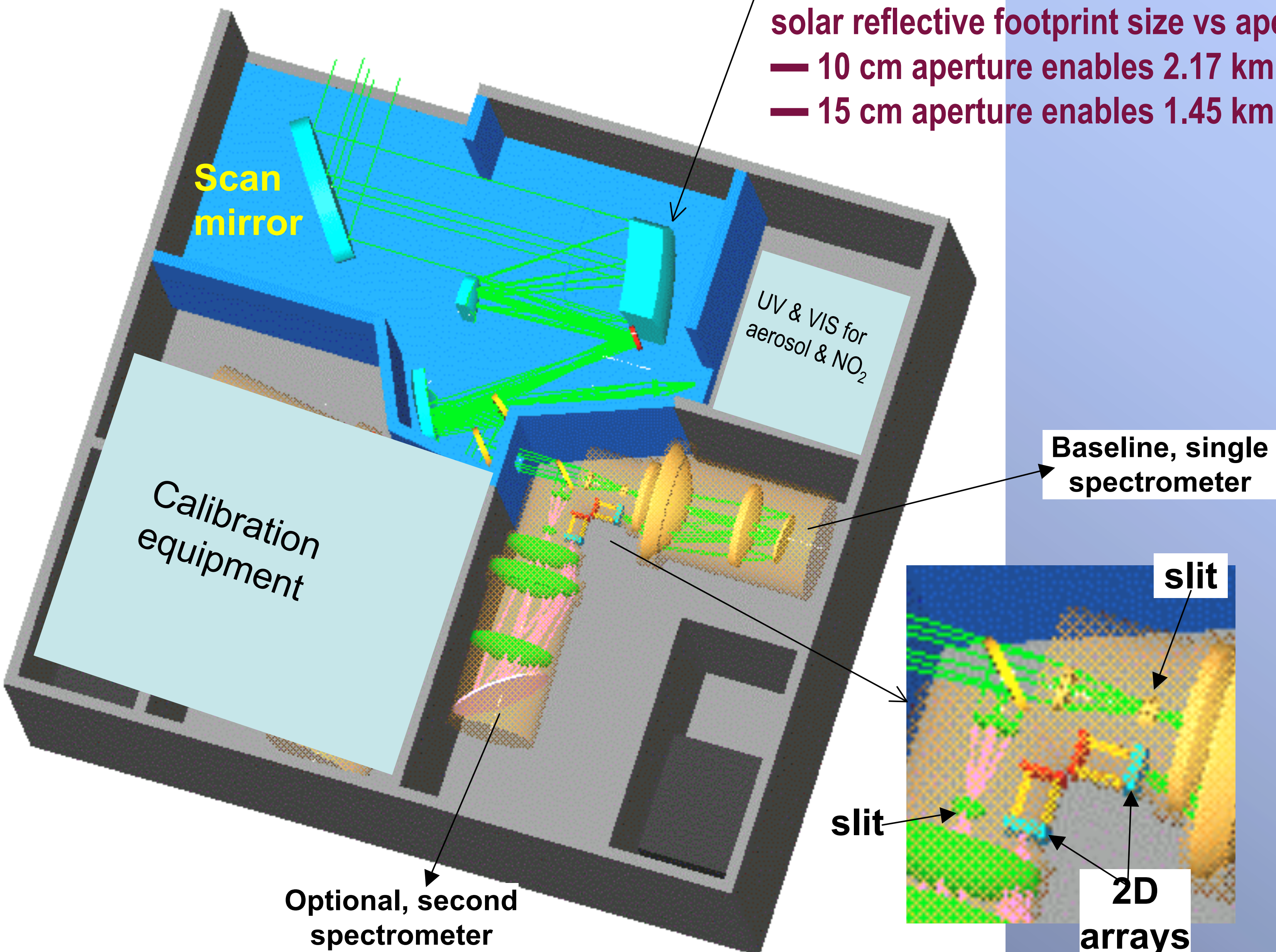
• Some CH_4 information should be available: this was a pollutio-oriented

Example concept for geo deployment of multiple spectrometers

- for cal sat 10 to 15 cm primary aperture is a reasonable choice

solar reflective footprint size vs aperture

- 10 cm aperture enables 2.17 km footprint
- 15 cm aperture enables 1.45 km footprint



Dedicated satellite vs Comm Sat piggyback

Excerpts from 1998 Geo Tropsat study

http://esto.nasa.gov/files/1999/Little_geotropsat.pdf

A dedicated remote sensing GEO satellite costs approximately $60-90M (RSDO catalog) including launch vehicle while a piggyback satellite ride to GEO can be obtained for approximately $7-15M including 2 years of operations, based on discussions between LaRC and vendors. [note: these are 1998 dollar values]

Practical considerations:

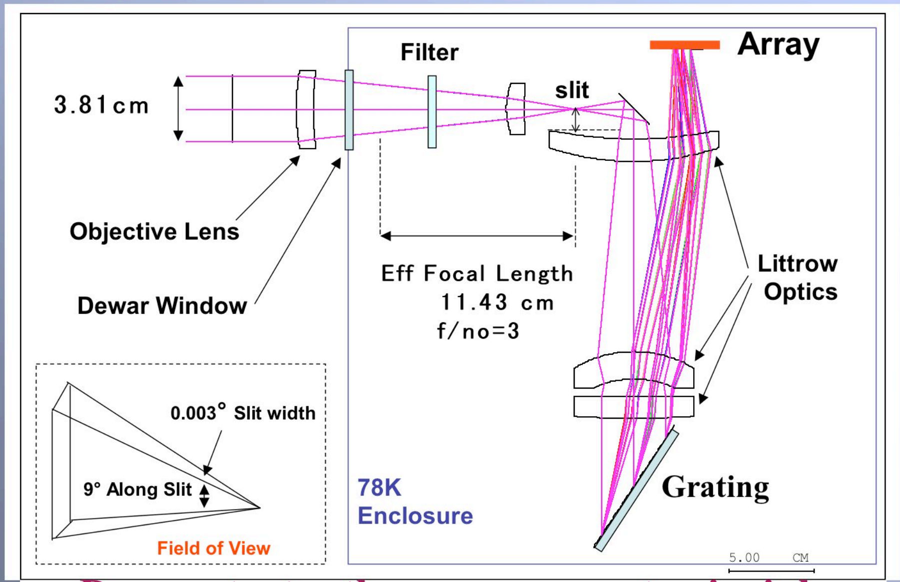
- Typically 10 to 20 comm sats launched per year
- Is there one scheduled to be placed near the CA longitude in the next few years?
  - If so, will it be possible to come to an arrangement to deploy CAL SAT on it?

Ready - to - go “TinyTIMS” — Clone to space-qualified parts

- Retain proven optical train and noise performance of “Demo” – a laboratory demonstration device
- Uses only one-half of a Hawaii HgCdTe (“Mer-Cad-Tel”) low-noise IR sensor
- Reset to a 3.57-micron-region for 1024 samples
- Imposes a large 3.2 km ELF (elemental footprint) at nadir; still small
- Improve precision by combining ELF’s into a larger 18 km region – but dodging clouds

- Several better choices, but proving them costs.

Laboratory demonstration grating mapping spectrometer (GMS) Optical schematic

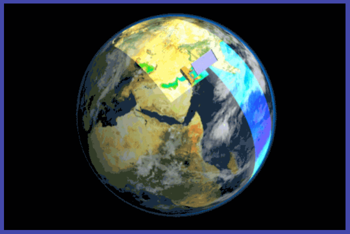


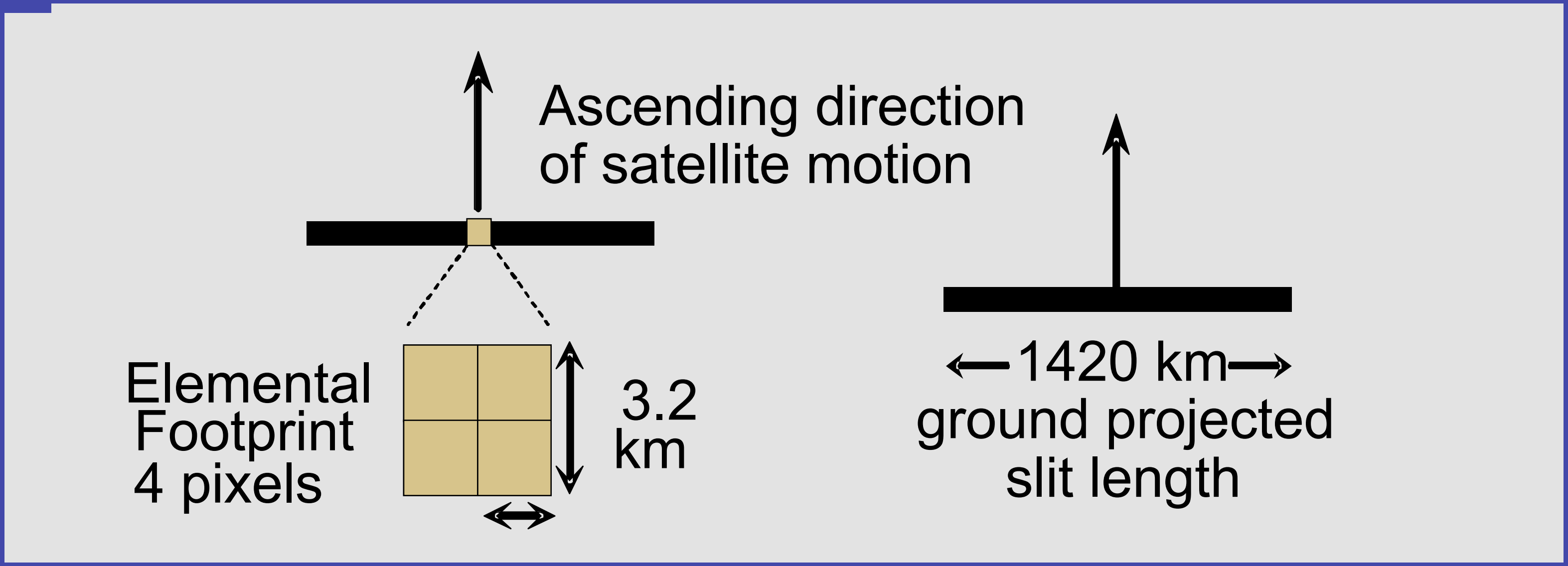
Demonstrates the measurement principle

•Would use clone of lab demo

•with field widened front end optics in the direction along the slit to provide

- –28° wide swath (~1420 km) and
- –3.2 km x 3.2 km SWIR footprint (4 physical pixels)

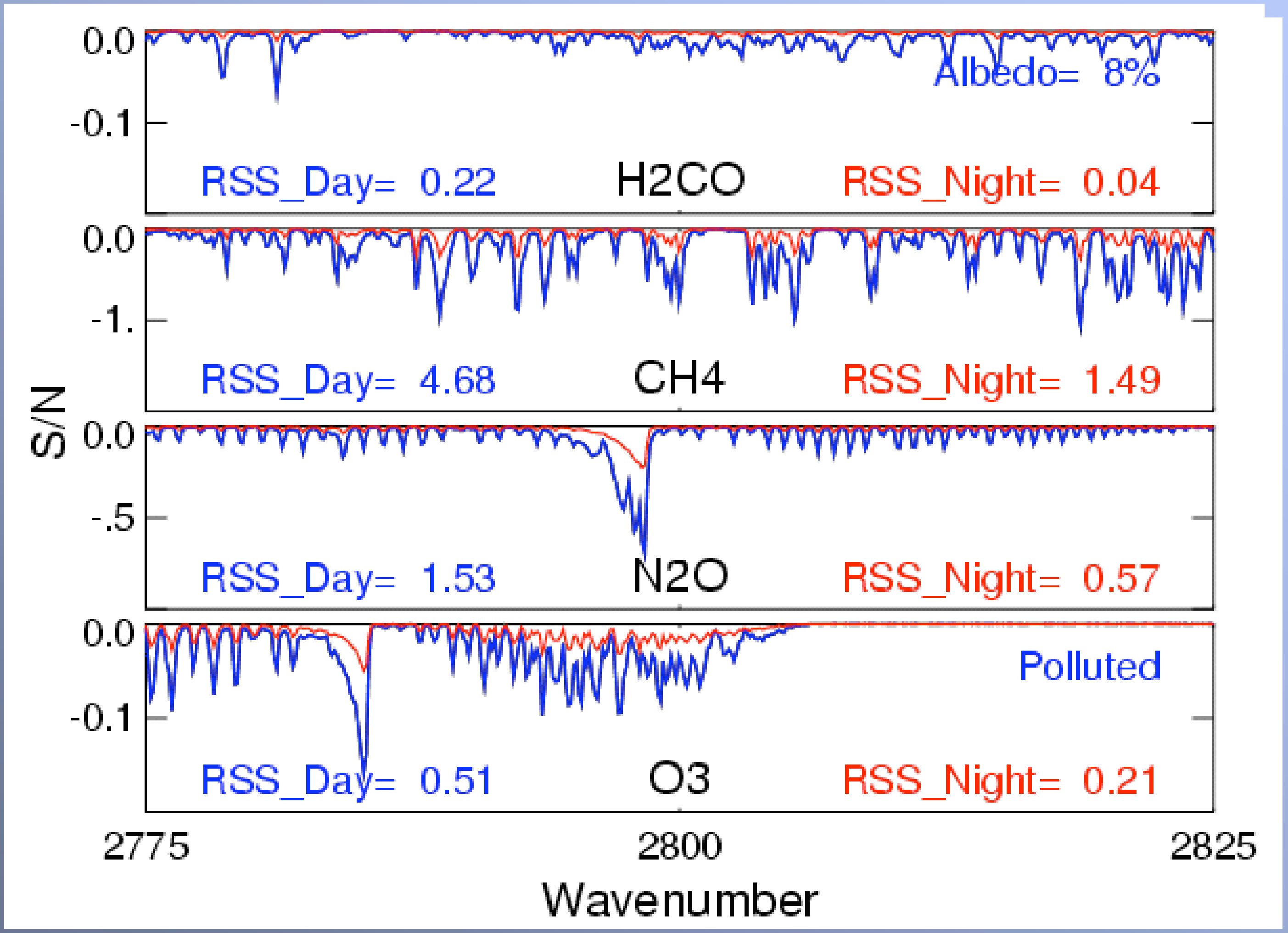




- **–Aim for near total overlap of ascending & descending nodes**
- **–Twice per day refresh**

spectral radiance change s SRC$_I$ in S/N due to

_ 1% change in spe cies column or surface albedo _ 1K change in surface temperature



retrieval approach: #1 use a first guess model to calculate expectation of radiance

#2 least squares fit the SRC $_I$ to the difference of measurement -model _ update model & iterate to convergence

Actually this description is an over simplification of the Rodgers optimal estimation retrieval approach

results of linear error analysis for single SWIR GMS

apply for an aggregated footprint AGF of 18.6 km x 18.6 km @ nadir

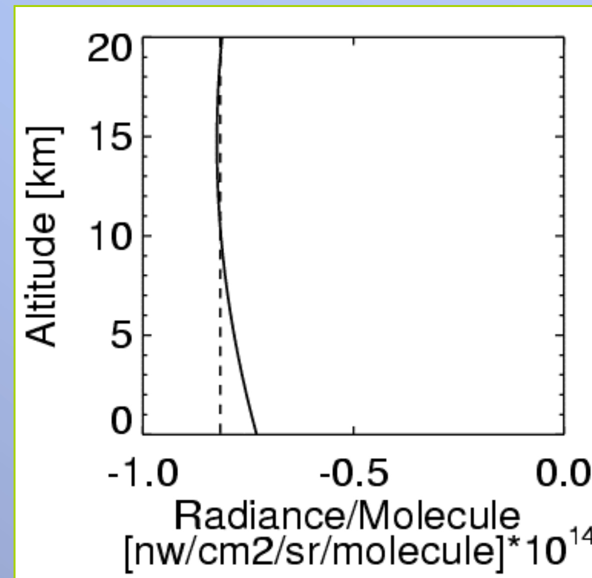
Table 4.1 LEA results for 3.57 micron SWIR region for column O_3, HCHO, CH_4, N_2O and surface parameters

State vector[2]	albedo = 8% daytime prc[1] (%)	albedo = 8% daytime A_{II}	albedo = 8% nighttime prc (%)	albedo = 8% nighttime A_{II}	albedo = 2% daytime prc (%)	albedo = 2% daytime A_{II}	albedo = 2% nighttime prc (%)	albedo = 2% nighttime A_{II}
O_3 P[3]	2.04	0.99	6.51	0.93	3.83	0.98	6.25	0.94
O_3 C	2.08	0.99	6.51	0.93	3.87	0.98	6.26	0.94
HCHO	5.97	1.00	33.4	0.89	13.6	0.98	29.3	0.91
H_2O	0.21	1.00	0.77	1.00	0.43	1.00	0.72	1.00
CH_4	0.22	1.00	0.81	1.00	0.45	1.00	0.76	1.00
N_2O	0.62	1.00	2.01	0.99	1.2	1.00	1.89	0.99
S T	0.01	1.00	1.15	0.99	0.05	1.00	1.16	0.99
S em	0.09	1.00	5.91	0.65	0.32	1.00	5.97	0.64

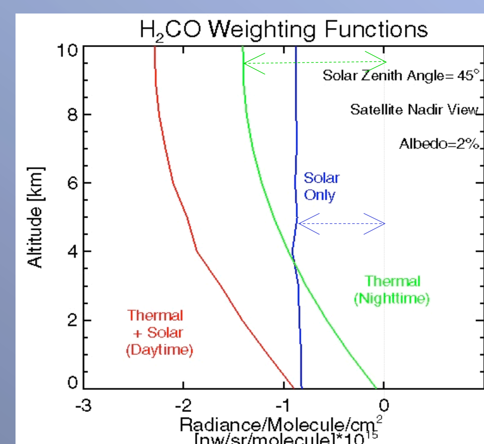
Notes **1** prc is retrieval precision and All the diagonal of the averaging matrix,

2 The state vectors are species columns and the surface parameters are S T the surface temperature and S em the surface emissivity (em =1-albedo). The S T precision unit is one deg Kelvin.

3 O_3 P is result for polluted case and O_3 C for clean case

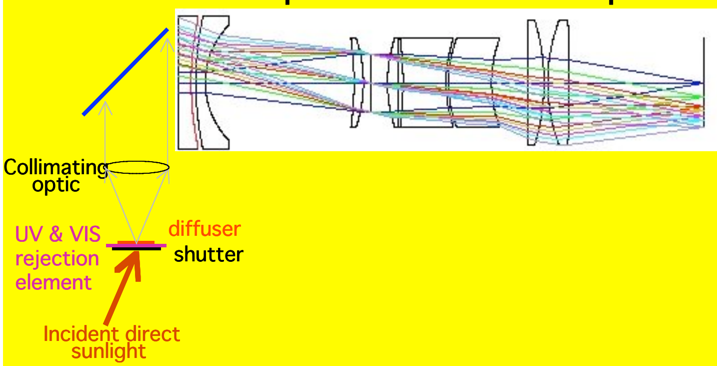


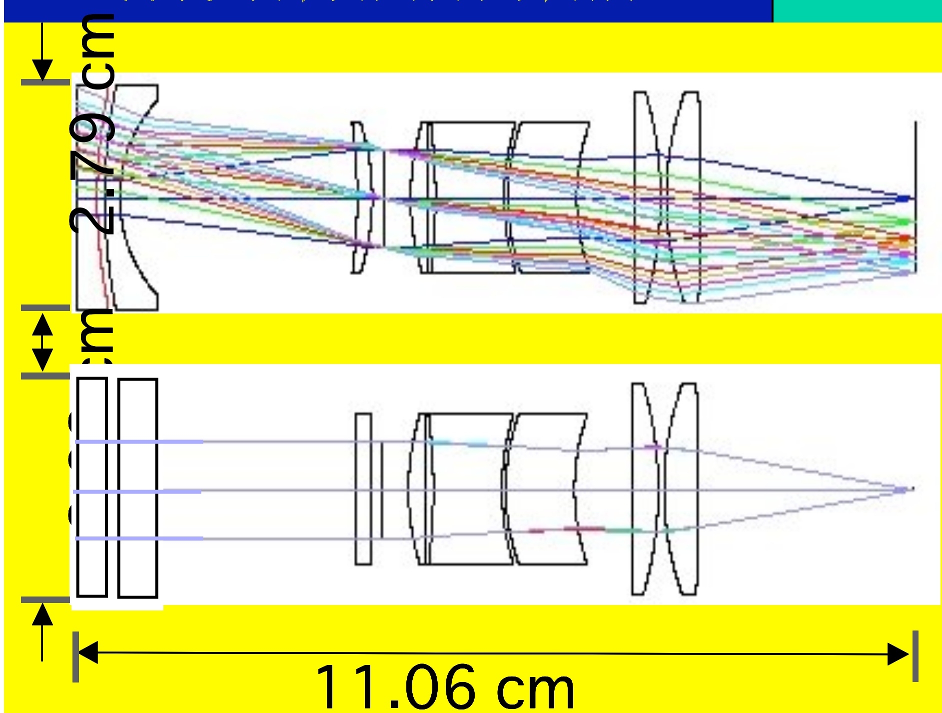
shows the O3 column retrieval sensitivity per molecule as a function of altitude for the daytime α=8% case.

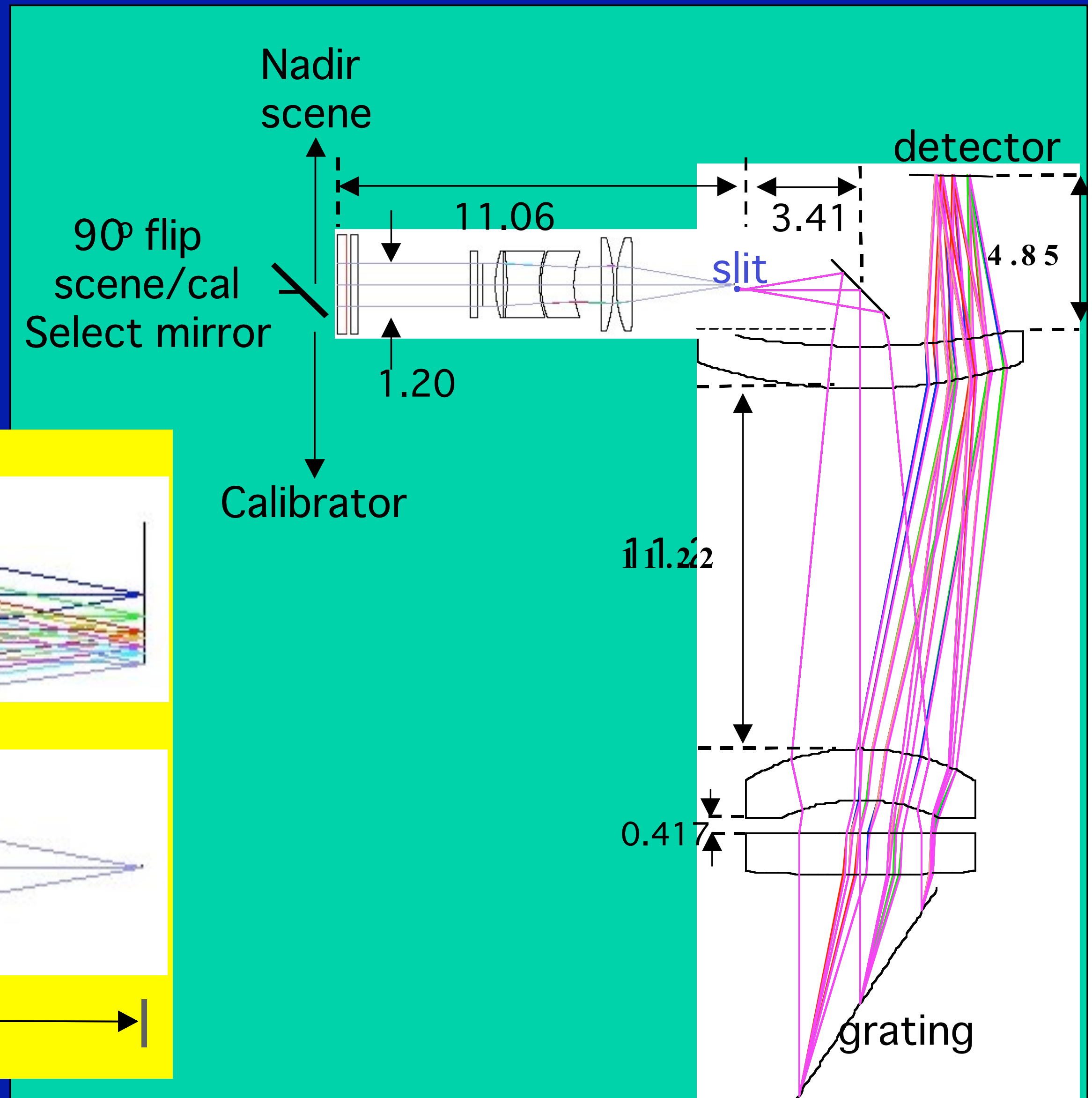


Lab demo optical design with crosstrack field widened input optics for spaceborne deployment

Solar spectral cal concept

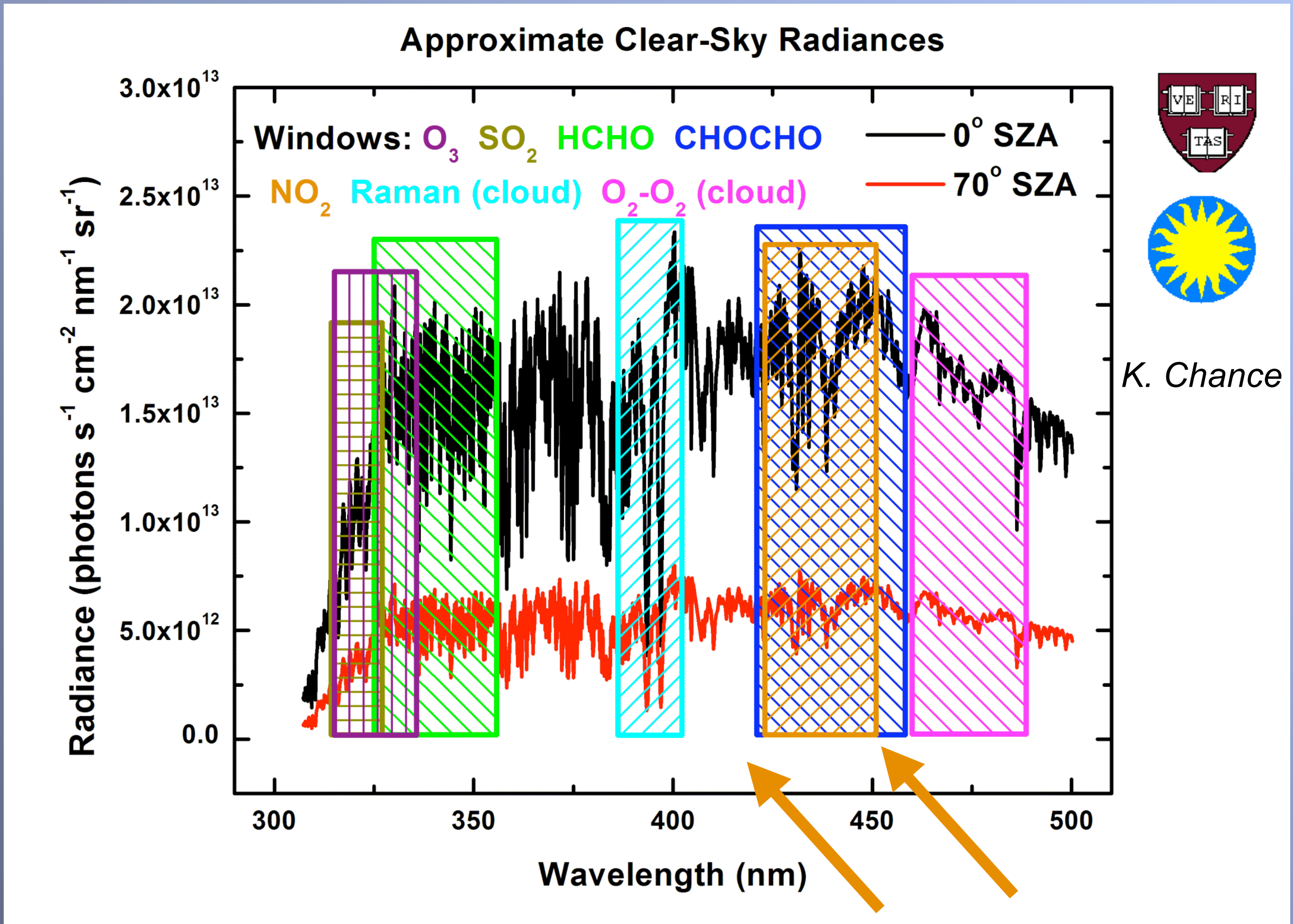






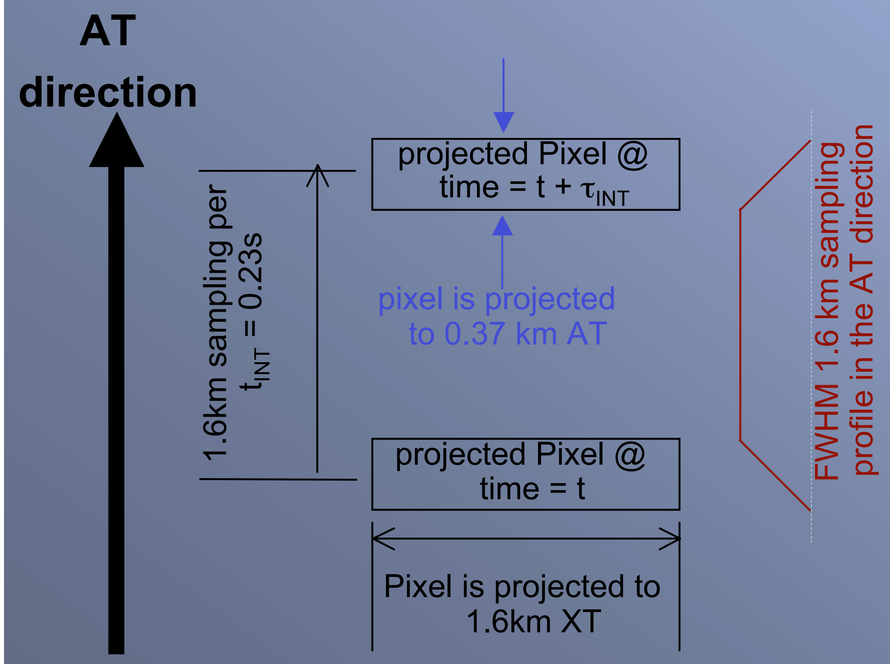
But what about NO_2?

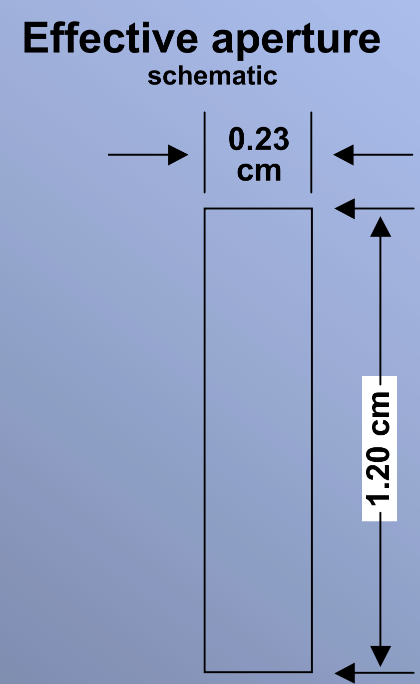
- TIMS infrared-instrument design can be readily reapplied to the NO2 region around 400 nm:
- ~4 microns to ~0.4 microns



The Leo Tiny TIMS NO_2 measurements (1 of 2)

- Baselining 18 μm pixels with 512 crosstrack and using 660 in the spectral direction to obtain spectra with 0.3 nm resolution on the 420 to 490 nm region
- Assuming an NPOESS orbit the anamorphic fore optics project a single 18 μm x 18 μm pixel to ground at nadir with dimensions 1.6 km crosstrack (XT) and 0.37 km along track level (AT)
- The anamorphic fore optics effective aperture dimensions are 0.28 cm XT & 1.2 cm AT
- The throughput = 2.83E-07 sr cm^2 [there follows 2 equivalent calculations, eg, Liouville's theorem]
  - = ΩA where with NPOESS altitude Z = 829 km Ω = (1.6/z)*(.37/z) and A = (.28cm)* (1.2cm) or equivalently
  - For an f/3 beam Ω = π*(1/6)^2 and A = (0.0018 cm)^2
- the AT sampling dimension of 1.6 km is established by the motion of the satellite & sets the integration time to τ_{INT} = 0.23s





Jkumer 12sep07

The Leo Tiny TIMS NO_2 measurements (2 of 2)

- 21610 photo-e are collected on each *(representative)* spectral sample (pixel) per each 1.6 km x 1.6 km elemental sampling footprint
- Including the effect of 30 e read noise this gives an $(S/N)^{-1}$ = 6.94E-03 which is a factor of 1.3 better than the requirement $(S/N)^{-1}$ = 8.99E-03 for NO_2 as given in the draft Harvard presentation "Global Monitoring of Tropospheric Pollution from Geostationary Orbit"
- **The Leo Tiny TIMS provides a 1.6 km spatial capability for NO_2 measurement!!**
- Parameters relevant to modeling the Tiny TIMS performance include:

radiance=1.5E13 photons/(s cm^2 sr nm)	throughput = 2.83E-07 sr cm^2	system transmission = 0.1
bandwidth = 0.28 nm	τ_{INT} = 0.23 s	quantum efficiency = 0.8

- It takes about 50 elemental sampling footprints to collect enough photo-e to satisfy the draft Harvard presentation "Global Monitoring of Tropospheric Pollution from Geostationary Orbit" requirement for $(S/N)^{-1}$ for CHOCHO

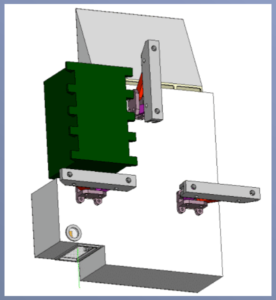
Key Measurement Attributes for geostationary deployment:

- High horizontal resolution (≤ 2-5 km)
  - ability to see through small cloud-free regions
- Regional coverage, with temporal resolution ≤ once per hour
  - provides information on synoptic scale development of pollution episodes
  - pinpoints emission sources
  - large puff releases
  - diurnal variations in emissions
- long range transport, several images per day
  - with high vertical resolution (several tropospheric layers)
    - including boundary layer if possible
  - multi-layer measurements on several per day basis tracks long range transport into and out of region
    - reveals geographical origins of pollutants & their contribution to region air quality
- Air quality species of major interest - O_3, HCHO, NO_2, CO
- Major climate change species - CH_4, CO_2

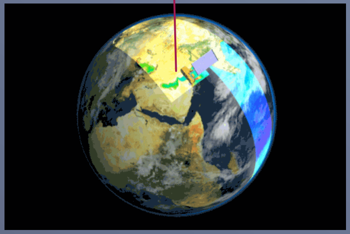
http://www.acd.ucar.edu/Events/Meetings/Air_Quality_Remote_Sensing/Reports/AQRSinputDS.pdf

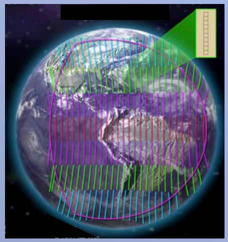
Guide to Instrument Concepts

- TinyTIMS: Fastest, least expensive way to powerful new low earth orbit measurements: O_3 and HCHO
- \- 20 kg, in the nano-sat to small-sat category
- Either “bridging technology” (2 year) or still-economical small 4-6 year Earth-tracking



- TIMS: a compact multi-species single-concept package:
  - HCHO and O_3 (tropospheric resolution)
  - ideal mate for a very compact, inexpensive UV sensor
  - CO and CH_4 with vertical tropospheric resolution
  - modest-accuracy CO_2 added inexpensively
  - Most/All(?) of GACM global tropospheric chemistry recommendation





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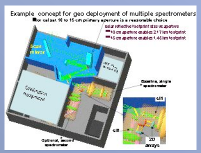


Performance Data

TIMS 4-channel (2.3, 2.1, 4.7 & 9.5 µm) instrument quad chart

Measurements: • footprint size @ nadir: smallest = 1.6 km @ 2.1& 2.3 µm, 3.2 km @ 4.7 µm & 6.4 km @ 9.5 µm

• can be aggregated to 9.6 x 9.6 km footprints to reduce TM to ~ 3.6 mbps

• wide swath for twice daily global coverage on 2-dimensionally contiguous footprints

• threshold spectral range $\nu_1 \rightarrow \nu_2$, resolution ($\Delta\nu$) & NEdN characteristics

channel	$\nu_1 \rightarrow \nu_2$ (cm^{-1})	$\Delta\nu$ (cm^{-1})	NEdN (nW/(cm^2 sr cm^{-1}))
~ 2.3 µm	4281→4301	0.13	1.0[A]
~ 2.1 µm	4775→4797 [B]	0.15	1.0
~ 4.7 µm	2112→2160	0.20	1.0[A]
~ 9.5 µm	1043→1075	0.10	2.0[X]

Notes: A- albedo=0.1 for reflective channels & @ 260K scene temperature for emissive channels; B- this range to be reviewed (TBR); X- Listed for stictly instrument noise, actual NEdN will be dominated by temperature model uncertainty and will be a factor 5 larger, however that is still a factor 5 < the TES NEdN

Tables of LEA results for 3-layer CO retrieval

Daytime LEA results for layered CO retrieval

parameter	Retrieval precision %	A_{II}	Rss_SNR
CO 0 – 2km	8.4	0.89	0.27
CO 2km – 6 km	4.3	0.97	1.13
CO 6 km –22km	2.3	0.99	1.6
Surface reflectance	.03	1.0	71.5

Nighttime LEA results for layered CO retrieval

parameter	Retrieval precision %	A_{II}	Rss_SNR
CO 0 – 2km	24	0.11	0.20
CO 2km – 6 km	6.7	0.93	1.09
CO 6km - 22km	2.5	0.99	1.56
Surface reflectance	0.59	1.0	63.0

Retrieval expectations:

CO with vertical information content DFS > 3.0

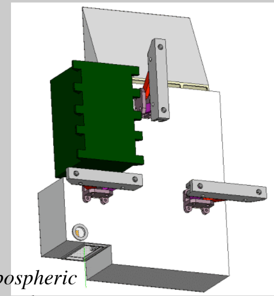
O_3 with DFS >or= that of TES (no 3.57 micron!)

CH_4 column the order 1 to 2% precision; some vertical

CO_2 column the order 1 to 3% (Normalizing)

N_2O column information (Normalizing gas)

Useful H_2O BL information



Tropospheric Infrared Mapping Spectrometer concept, courtesy J. Kumer, Lockheed-Martin

IR mapping

[HCHO]

$[O_3]$ (total + profile)

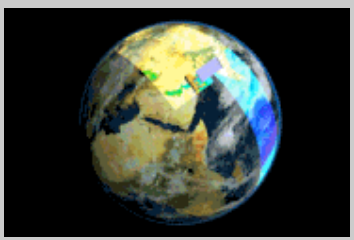
UV mapping

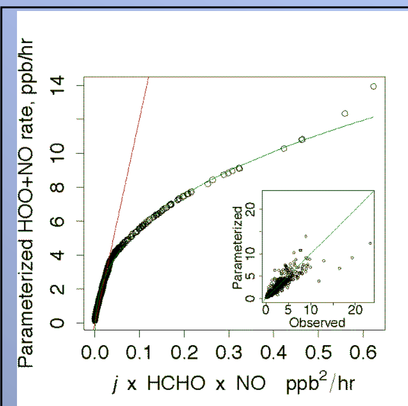
$[NO_2]$

UV

$[O_3]$ (partial)

$P°_{O_3}$





UV monitor

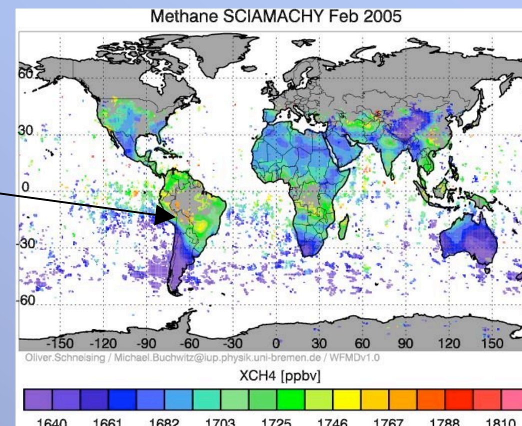
[HCHO] monitor

[NO] monitor

$$\left.\right\} \xrightarrow{f_1} P°_{O_3} \xrightarrow{\gamma} P_{O_3}$$

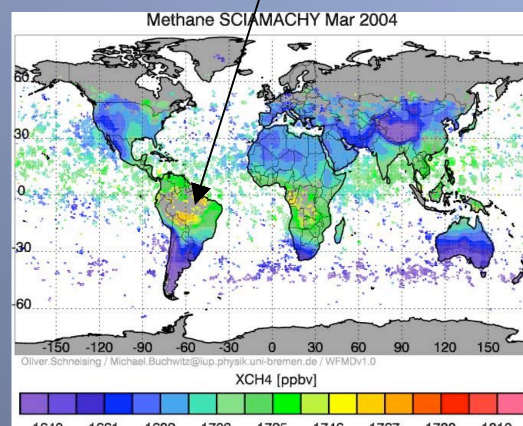
Promise of Reflective IR in recent SCIAMACHY retrievals: Tropical Methane

- Do we understand controls on seasonal hotspots like the Pantanal (or African wetlands)?
- http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/
- After mirror-icing dealt with

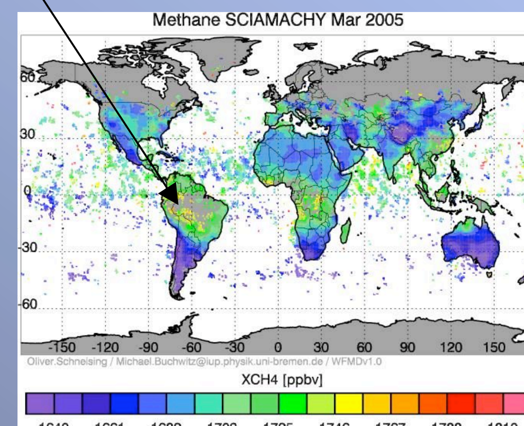


Feb 05

How much more would we see with 1.5-6 km footprints?



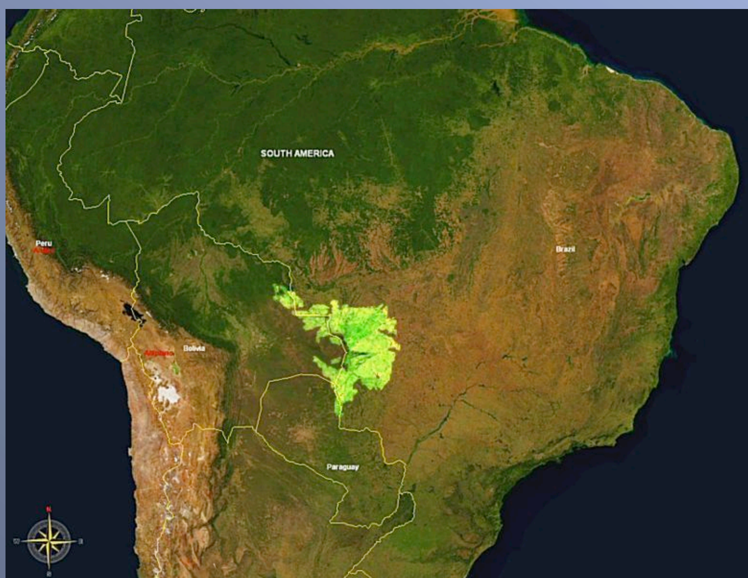
Mar 04

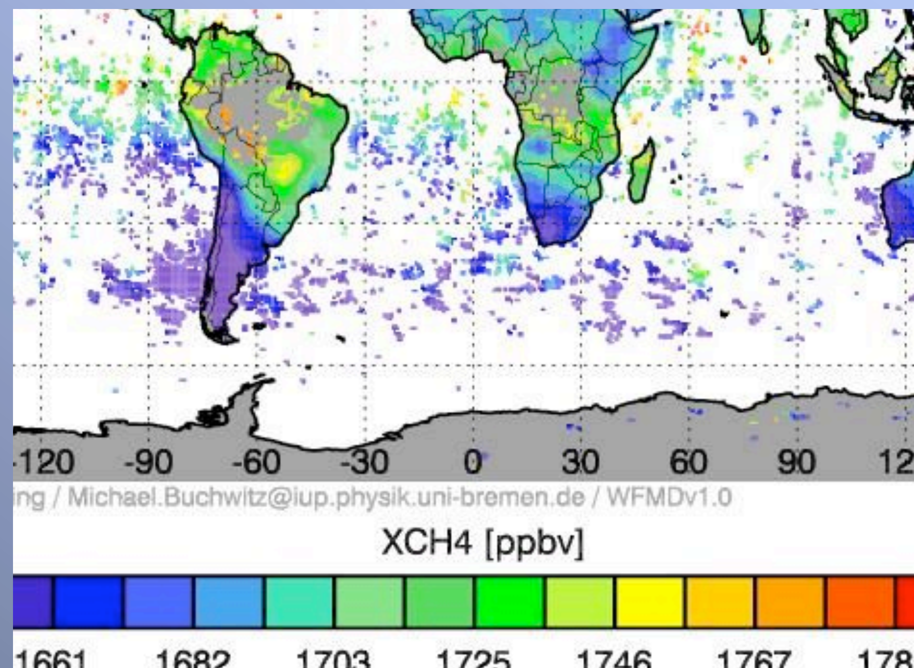


Mar 05

Pantanal End-of-Flood and CH_4 Emissions

- Very new reanalysis of SCIAMACHY data
- Sciamachy Feb ’02 CH_4 and Pantanla extent. Note also high CH_4 around wetter (southern equatorial) rainforest area





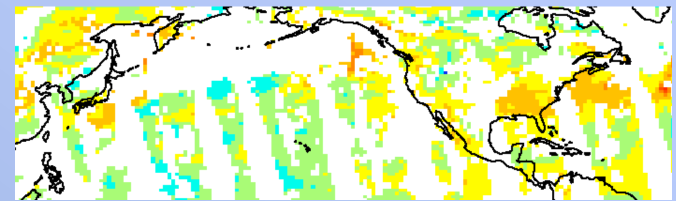
Key Measurement Attributes for geostationary deployment:

- High horizontal resolution (≤ 2-5 km)
  - ability to see through small cloud-free regions
- Regional coverage, with temporal resolution ≤ once per hour
  - provides information on synoptic scale development of pollution episodes
  - pinpoints emission sources
  - large puff releases
  - diurnal variations in emissions
- long range transport, several images per day
  - with high vertical resolution (several tropospheric layers)
    - including boundary layer if possible
  - multi-layer measurements on several per day basis tracks long range transport into and out of region
    - reveals geographical origins of pollutants & their contribution to region air quality
- Air quality species of major interest - O_3, HCHO, NO_2, CO
- Major climate change species - CH_4, CO_2

http://www.acd.ucar.edu/Events/Meetings/Air_Quality_Remote_Sensing/Reports/AQRSinputDS.pdf

Concept Guide

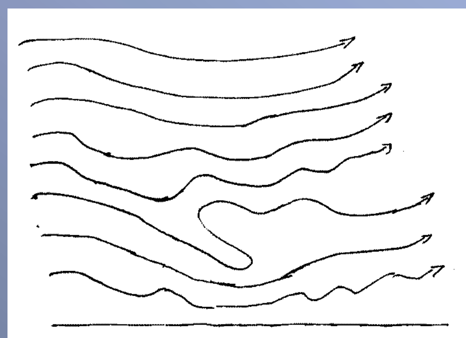
- Our (shared) vision: tracking ozone and its production



$\boxed{\text{UV monitor}}$
$\boxed{\text{[HCHO] monitor}}$
$\boxed{\text{[NO] monitor}}$

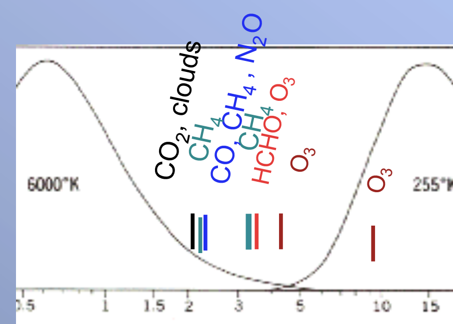
$$\left.\right\} \xrightarrow{f_1} P^{\circ}_{O_3} \xrightarrow{\gamma} P_{O_3}$$

- Sensing BL smog ozone rapidly and inexpensively

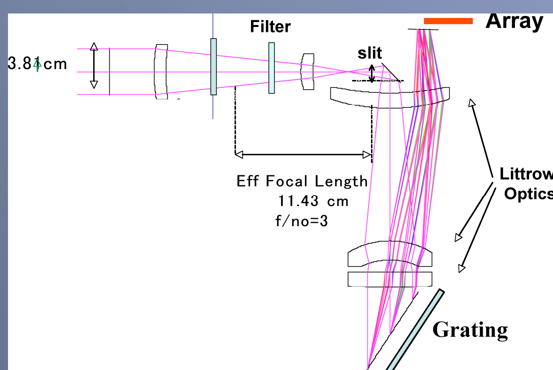


- Sensing ozone production

- New ways of highlighting smog (LT) ozone



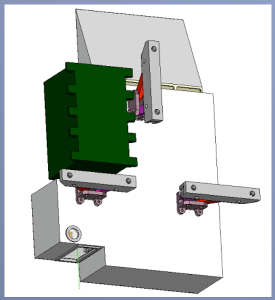
- New wavelength windows in the "dark regions"



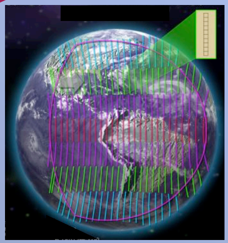
- Newly simple-design instrumental techniques

The End

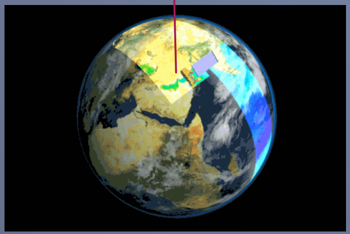
- TinyTIMS: Fastest, least expensive way to powerful new low earth orbit measurements: O_3 and HCHO
- - 20 kg, in the nano-sat to small-sat category
- Either "bridging technology" (2 year) or still-economical small 4-6 year Earth-tracking

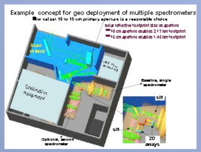


- TIMS: a compact multi-species single-concept package:
  – HCHO and O_3 (tropospheric resolution)
  – ideal mate for a very compact, inexpensive UV sensor
  – CO and CH_4 with vertical tropospheric resolution
  – modest-accuracy CO_2 added inexpensively
  – Most/All(?) of GACM global tropospheric chemistry recommendation



- GEOTIMS: similar compact multi-species single-concept package for piggyback, 87 kg
  – HCHO and O_3 (tropospheric resolution)
  – ideal mate for a very compact, inexpensive UV sensor
  – CO and CH_4 with vertical tropospheric resolution
  – modest-accuracy CO_2 conceivable





Supporting the NASA Mission

The End

Dedicated satellite vs Comm Sat piggyback

Excerpts from 1998 Geo Tropsat study

http://esto.nasa.gov/files/1999/Little_geotropsat.pdf

A dedicated remote sensing GEO satellite costs approximately $60-90M (RSDO catalog) including launch vehicle while a piggyback satellite ride to GEO can be obtained for approximately $7-15M including 2 years of operations, based on discussions between LaRC and vendors. [note: these are 1998 dollar values]

Practical considerations:

- Typically 10 to 20 comm sats launched per year
- Is there one scheduled to be placed near the CA longitude in the next few years?
  - If so, will it be possible to come to an arrangement to deploy CAL SAT on it?